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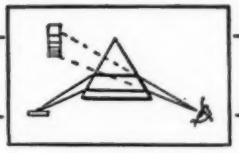

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THE OPTICAL SOCIETY OF AMERICA was organized in 1916 "*to increase and diffuse the knowledge of optics in all its branches, pure and applied, to promote the mutual interests of investigators of optical problems, of designers, manufacturers and users of optical instruments and apparatus of all kinds and to encourage cooperation among them.*" It aims to serve the interests of all who are engaged in any branch of optics from fundamental research to the manufacture of optical goods.

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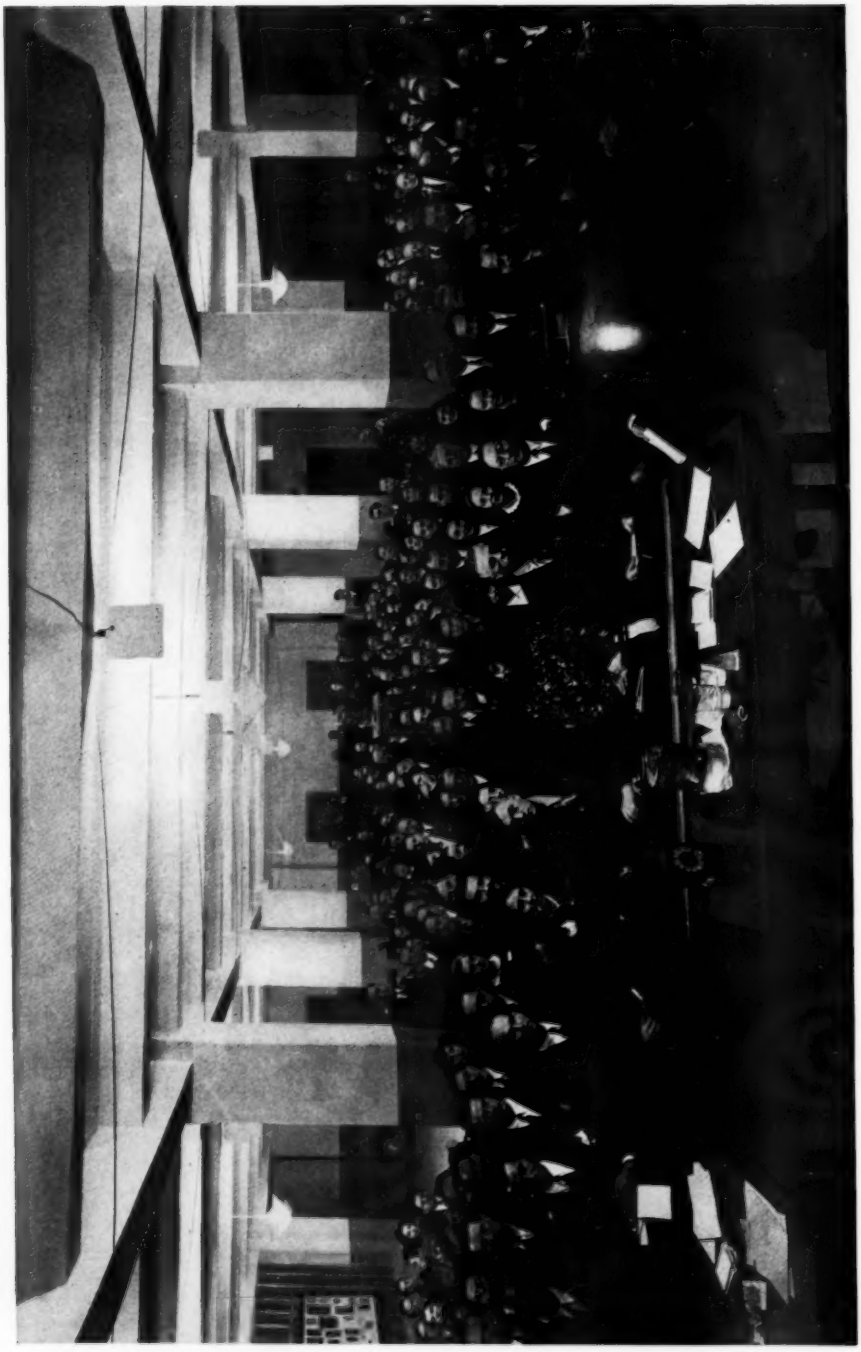
The Society holds two meetings per year: An annual meeting in the autumn and a midwinter meeting jointly with the American Physical Society.

For further information concerning the Optical Society of America address the Secretary, Dr. L. B. Tuckerman, National Bureau of Standards, Washington, D. C.



The Inter-Society Color Council at its seventh annual meeting held at the Electrical Testing Laboratories, New York, February 24, 1938.

Journal of the
OPTICAL SOCIETY *of* AMERICA

VOLUME 28 OCTOBER, 1938 NUMBER 10

The Inter-Society Color Council*

IT is appropriate that the five papers presented at the afternoon program of the Seventh Annual Meeting of the Inter-Society Color Council should appear in this journal. First, the Optical Society was active in the organization of the Inter-Society Color Council and has maintained an active interest since that time; second, the Optical Society unofficially cosponsored the Seventh Annual Meeting, held at the Electrical Testing Laboratories on February 24, 1938, just prior to its own meetings at Columbia University, February 25–26, 1938; and third, the five papers relate to methods and applications of spectrophotometry, subjects which lie in the field of optics.

The Inter-Society Color Council grew out of a color conference and exhibit sponsored by the Revision Committee of the U. S. Pharmacopoeia in Washington, May 1930, Professor E. N. Gathercoal, in charge. On February 26, 1931, a preliminary conference held at the Museum of Science and Industry in New York City considered the matter of organizing an Inter-Society Committee on Color Specification. This conference was attended by representatives of fourteen national associations and by sixteen individuals, Dr. L. A. Jones, acting as chairman. The one person who probably had most to do with the form which the Council took was the late Mr. I. G. Priest. He presented to the group a resolution which had been discussed and adopted by the Executive Committee of the Optical Society of America: "It is the sense of the Executive Council of the Optical Society of America that the need for better organization of those interested in the description and specification of color which found expression at the 'Color Conference' held in Washington, May 14, 1930 can best be met by the formation of a joint council consisting of officially designated representatives of the several national societies and associations interested in the description and specification of color."

After a lengthy informal discussion ideas began to crystallize and finally almost complete unanimity of opinion was reached. It was the sense of the meeting that an Inter-Society Color Council be formed, and that a meeting should be called at which time the Council should form a permanent organization. On September 21, 1931 the first annual meeting was held at which Professor E. N. Gathercoal was elected chairman.

Membership in the Council, under the Articles of Organization and Procedure adopted in 1935, is held in three classes: Member bodies, individual members, and sustaining members. Each member body may elect up to 10 delegates to represent it on the Council, of which three are designated as voting members. The individual membership group, when it numbers over 25, elects three voting members to the Council, and is thereby represented on the basis of a member body. As shown by the last annual report, 33

* This historical note on the Inter-Society Color Council was prepared by the Secretary of the Council at the request of the Editor.

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individuals, and the following nine national associations hold membership in the Council:

American Association of Textile Chemists and Colorists
American Psychological Association
American Society for Testing Materials
Illuminating Engineering Society
National Formulary, of the American Pharmaceutical Association
Optical Society of America
Technical Association of the Pulp and Paper Industry
Textile Color Card Association of the U. S., Inc.
U. S. Pharmacopoeial Convention

Since 1931 the following meetings have been held:

Annual	Date	Place*	Chairman
1st	1931, Sept. 21	Museum of Science and Industry	L. A. Jones, Acting
2nd	1932, Dec. 28	Columbia University, College of Pharmacy	E. N. Gathercoal
	1933, Feb. 25	Columbia University, College of Pharmacy, Joint Meeting with O. S. A. Colorimetry Committee	A. E. O. Munsell
3rd	1933, Dec. 28	Columbia University, College of Pharmacy	L. A. Jones, Vice Chairman†
4th	1935, Feb. 21	Columbia University, College of Pharmacy	L. A. Jones, Vice Chairman†
5th	1936, Feb. 20	Waldorf-Astoria Hotel	M. Rea Paul
6th	1937, Feb. 25	Waldorf-Astoria Hotel, afternoon—I. E. S. theater, evening	M. Rea Paul
7th	1938, Feb. 24	Electrical Testing Laboratories	Forrest Lee Dimmick

From the beginning, the work of the Council in coordinating and giving advice on problems submitted by member bodies has been accomplished through committee work. Chief among the problems has been that of the U. S. Pharmacopoeia for "a means of designating colors . . . sufficiently standardized to be acceptable to science, sufficiently broad to be appreciated and usable by science, art, and industry, and sufficiently commonplace to be understood, at least in a general way, by the whole public." The basis for the answer to this problem was contained in Dr. I. H. Godlove's report to the Council for the 1933 Committee on Measurement and Specification. Since that time, under Dr. Deane B. Judd's chairmanship, the work has been continued and expanded. For the past two years the American Pharmaceutical Association jointly with the U. S. Pharmacopoeial Revision Committee has had a research associate at the National Bureau of Standards working with Dr. Judd in following out the recommendations of the Council and completing the work on this system of color names. It is planned to use this system both in the U. S. Pharmacopoeia and in the National Formulary.

In 1933 the Council adopted a resolution regarding the compilation of a list of "Who's Who in Color." The list has been compiled, and was published by the Council in June 1938. Surveys of color terms, color tests, and color problems, have been the subject of much work by subcommittees of each cooperating association. Partial reports have already been published. On October 16, 1933 the first of a series of news letters was published, distribution being to delegates and individual members.

Early meetings of the Council were business meetings, at which reports of working committees were read and discussed. In 1936 the first of a series of public lectures was added. That year over 500 persons crowded the Astor Gallery at the Waldorf-Astoria to hear "Three Lectures on Color" given through the courtesy of the International Printing Ink Corporation. Cooperation of the Technical Association of the Pulp and Paper Industry provided the meeting place. In 1937, the New York chapter of the Illuminating Engineering Society cooperated in giving two evening lectures on color in lighting.

In 1938 a third, and technical session, was added to the program. Reports of committee activities—the real backbone of the Council—were handled at the morning business session; the usual public lectures were given in the evening; and a technical session, at which were presented the five invited papers which appear in this journal, was held in the afternoon. The titles of these papers are as follows:

"History of the Design of the Recording Spectrophotometer" by Arthur C. Hardy
"Construction of the General Electric Recording Spectrophotometer" by J. L. Michaelson

* All of these meetings were held in New York City.
† The chairman, Mr. A. E. O. Munsell, had resigned.

"Calibration and Operation of the General Electric Recording Spectrophotometer of the National Bureau of Standards" by Kasson S. Gibson and Harry J. Keegan

"Application of Spectrophotometric Data in the Printing Ink Industry" by Carl E. Foss

"Designation of Filters for Theatrical Lighting" by Deane B. Judd

Because of the current need for information on the subject, four of the papers were centered around the Hardy General Electric Recording Spectrophotometer, its design and use; the fifth paper is the answer proposed to one of the several problems before the Council at the beginning of 1937.

The Inter-Society Color Council was formed "to stimulate and coordinate the work being done by the various societies, organizations, and associations leading to the standardization, description, and specification of color, and to promote the practical application of these results to the color problems arising in science, art, and industry." It grows in usefulness in proportion to the number of, and cooperation extended by, its member bodies. At present it can be said that this cooperation has been excellent. The offer made by the Board of Directors of the Optical Society of America to devote an issue of this journal to the publication of five papers given at the Seventh Annual Meeting of the Inter-Society Color Council, is representative of that type of cooperation, and is thoroughly appreciated by the Council.

DOROTHY NICKERSON
Secretary, Inter-Society Color Council

History of the Design of the Recording Spectrophotometer*

ARTHUR C. HARDY
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received July 5, 1938)

SPECTROPHOTOMETRY is an old art. Its birth occurred nearly eighty years ago during the decade that witnessed the synthesis of the first organic dyestuff. Although the dyestuffs industry and the art of spectrophotometry have grown up together, they have met only on rare occasions until recently. Indeed, spectrophotometry remained for years within the confines of the physical laboratory, where it was seldom employed in connection with problems that would be of interest to this audience. In these sheltered surroundings, the instrumental phase of the subject received the major attention; but, to discuss the development of the various types of spectrophotometers adequately, would consume more time than this portion of the subject deserves on the present program. In justice to those who may have anticipated a more general discussion, it should be mentioned that an excellent survey of this art can be found in the *Journal of the Optical Society of America* for 1925.[1]

My interest in spectrophotometry originated soon after I joined the staff of the Physics Department of the Massachusetts Institute of Technology in 1922. A previous connection with the Research Laboratories of the Eastman Kodak Company had stimulated an urge to investigate the problems connected with three-color reproduction; but, because color photography seemed to be in safe hands, I decided to investigate the corresponding problems in the field of color printing. Even the most cursory examination of these problems indicated that the type of color analysis which a spectrophotometer provides would be necessary. Although our optical laboratory was equipped with visual spectrophotometers of three different types, it did not appear that they would be suitable for the purpose. The scientific approach to color reproduction in the graphic arts was then almost virgin territory, and it seemed probable that a great mass of spectrophotometric data would be required. Indeed, when I compared the program that I had in mind with the American mortality tables, I was forced to conclude that my insurance policies would undoubtedly become claims long before the program could be completed.

The only escape from this situation seemed to lie in the direction of developing a more rapid method of spectrophotometry. There was little hope of decreasing the time required for a spectrophotometric analysis with instruments of the visual type. This type of instrument requires that the reflectance of the test sample be determined with high precision under illumination by homogeneous light of some thirty different wave-lengths within the visible region of the spectrum. Since at least five settings are usually necessary at each wave-length, the possibility that an instrument could be devised to determine these data and record them automatically seemed worthy of investigation. Indeed, Gibson[2] had already described a spectrophotometer in which the human eye was replaced by a photoelectric cell. Although this instrument was not of the recording type and was not appreciably more rapid than the visual type of spectrophotometer, it did demonstrate that the sensitivity of a photoelectric cell was of the order required. Unfortunately, the sensitivity of such cells was at that time inadequate at the red end of the spectrum. As a consequence, it seemed necessary to investigate the characteristics of light-sensitive cells of other types, which might either supplement the photoelectric cell at the red end of the spectrum or might preferably encompass the entire visible region. Of the various types then available, the thalofide cell made by the Case Laboratories seemed to hold the greatest promise. Probably the first actual step in our develop-

* Invited paper presented at the seventh annual meeting of the Inter-Society Color Council held at the Electrical Testing Laboratories, New York, February 24, 1938.

[1] Report of the Optical Society of America Progress Committee on Spectrophotometry, J. Opt. Soc. Am. **10**, 169 (1925).

[2] Nat. Bur. Stand. Sci. Pap. No. 349 (1919); also J. Opt. Soc. Am. **2**, 3, 23 (1919).

ment program was the acquisition of two thalofide cells in December, 1922, for the purpose of learning as much as possible about their characteristics.

These thalofide cells were found to have a relatively high electrical resistance which varied upon exposure to light in a manner that defied calibration. This erratic behavior was not altogether unexpected. Neither was it a great disappointment because of the almost certain necessity of employing vacuum tube amplifiers, which at that time were almost as erratic. I presume that if we had encountered a light-sensitive cell and amplifier which would hold a calibration long enough to make an accurate measurement, we might have been more reluctant to embrace the additional complications required by the null method.

Since the term *null method* is frequently used today in connection with devices employing two light-sensitive cells, it is necessary to define the meaning of the term as it was used by Gibson and by us. This definition can be stated most conveniently by reference to the procedure employed with spectrophotometers of the visual type. In this case, the observer views a photometric field, one-half of which is filled with light from the test sample and the other half with light from the standard of comparison. By altering the intensity of one (or more frequently both) of the beams, the observer endeavors to match the brightness of the two halves of the field. None of the difficulties of heterochromatic photometry are encountered during this operation because, in spectrophotometry, both halves of the field are illuminated by light of the same spectral quality. It is conceivable, however, that the principle of the flicker photometer could be applied to spectrophotometers of the visual type. In this case, the same field of view would be illuminated alternately by light from the test sample and by light from the standard. After choosing a convenient frequency of alternation, the observer would endeavor to adjust the intensity of one or both of the beams until the magnitude of the flicker is at a minimum. The data obtained by either of the methods just outlined are independent of the characteristics of the eye of the observer. In other words, both procedures are null methods in the sense in which the term is used here. Although a visual spectrophotometer of the first type does not readily lend itself to conversion into a photoelectric instrument, the second type of instrument may be so converted merely by using a light-sensitive cell in the place of the eye. It is almost axiomatic that, if two beams of light of the same spectral quality and state of polarization impinge alternately from the same direction upon the same area of a light-sensitive cell, the two beams may be adjudged equal when the fluctuations in the response of the cell are at a minimum. This is the photoelectric counterpart of the null principle of visual spectrophotometry.

The first scheme embodying the above principle included a recording attachment operated by the amplified cell current. Since the output of the amplifier is an alternating current, except at the time of a photometric balance, it seemed feasible to employ a detector tube to operate a relay whenever no signal was received. We proposed at that time to move a platen containing the recording paper by means of a direct mechanical connection with the driving mechanism which was to change the wave-length continuously throughout the visible spectrum. The recording stylus was likewise to move continuously by means of a mechanical connection with the device for controlling the relative intensities of the two beams under comparison. Since the relative intensities were to be varied in a cyclical manner, the relay would operate each time the photometric balance was attained. By energizing a magnet, the relay would cause the stylus to make a dot on the recording paper. The spectrophotometric record would thus consist of a series of points through which a smooth curve could later be drawn.

The instrument described above was never completed for the reason that, during the course of its construction, an improved method of recording was devised. By making use of the fact that the phase of the signal current shifts through 180° at the point of balance, a motor whose field coils were excited by the amplified cell current was caused to rotate in one direction when the photometer was out of balance on one side, in the opposite direction when out of balance on the other side, and to cease its rotation when at the point of balance. By cou-

pling this motor to the device for regulating the relative intensities of the two beams, the motor was caused to make its own photometric setting. After making a setting, it endeavored to hold the position of photometric balance while the wave-length was changed continuously throughout the spectrum. This arrangement permitted the stylus to be in contact with the paper at all times; and the result was a smooth spectrophotometric curve rather than a series of points.

The construction of the instrument just described was virtually completed during the latter part of 1926, although difficulties were still encountered with the amplifier. The caesium type of photoelectric cell had just been developed, which solved the problem of obtaining a single cell capable of encompassing the entire visible spectrum. Its adoption introduced some new problems in the amplifier which need not concern us here. Suffice it to say that the first spectrophotometric curve drawn completely by automatic means was obtained on January 18, 1928, and that a description of the instrument was prepared for publication a few months later.[3]

The first few months of operation of this instrument were very exciting. We measured the color of everything within sight and then went out to look for more samples.[4] The instrument was found to operate with such rapidity that it generally took less time to make a measurement than it did to decide whether such a measurement was likely to be significant. This period provided us with considerable experience in the operation of the instrument and with a background concerning the colors of natural objects which was later to prove useful in connection with the theory of three-color reproduction.

The idea of an instrument capable of measuring color automatically proved to be very intriguing to the lay mind. Descriptions of this instrument began to appear even in the daily papers shortly after the first scientific disclosure. This had the result of bringing hundreds of visitors to our laboratory and brought inquiries by mail from an even greater number. For the first time we realized that virtually every industry is beset by color problems of one sort or another. In some industries, the preservation of color standards over long periods of time is a distinct desideratum. By evaluating the color of a test sample spectrophotometrically in terms of quantities and wave-lengths of light, an imperishable color record is obtained. In other industries, there is need for more insight into the phenomena associated with the mixture of dyes or pigments. In this case also, spectrophotometry simplifies the problem by resolving each color into its spectral components. This eliminates the complexities introduced by the visual mechanism of the human observer, who is unable by himself to make such a resolution.

Because numerous requests were received for an instrument patterned after our first model, arrangements for its commercial manufacture were made with the General Electric Company during the summer of 1928. This commercial instrument, although embodying the essential principles of the null method, included one change which experience with our laboratory model had shown to be desirable. The usual procedure in spectrophotometry had been to illuminate the test sample and standard by means of heterogeneous light, which was subsequently dispersed into its spectral components. Before constructing our laboratory model, we debated the possibility of interchanging the positions of the lamp and photo-cell in order that the test sample and standard might be illuminated by light of substantially a single wave-length. This possibility was discarded because of the difficulty in interpreting the results in the case of fluorescent samples. Experience with our laboratory model quickly demonstrated that it was highly important in most instances to avoid overheating the test sample by direct exposure to the undispersed radiant energy from the lamp. Since test samples exhibiting fluorescence under exposure to light within the visible range of the spectrum are relatively rare, the direction of light through the optical system of the commercial instrument was reversed.

We were never entirely satisfied with the accuracy of the results obtainable with our first laboratory model. Although its sensitivity was

[3] J. Opt. Soc. Am. and Rev. Sci. Inst. **18**, 96 (1929).

[4] *Editor's Note:* When this paper was presented, the author exhibited lantern slides made from many of these spectrophotometric curves to which he here refers.

usually adequate for the direct comparison of two samples exhibiting only a small color difference, there was little in reserve.[5] One of the limitations on the accuracy of the instrument could be traced to the optical system, which caused the two beams under comparison to traverse a different set of optical parts. It was therefore essential that the optical parts be kept scrupulously free from dust; and it was also necessary to calibrate the photometric scale at each wave-length, because of the presence of a silvered surface in one of the paths. As a consequence, we turned our attention during 1931 to the design of a new optical system. The desirability of sending both beams through the same optical parts suggested the use of a polarization photometer in which one of the beams under comparison is polarized in one plane and the other beam is polarized in a plane at right angles thereto. A new instrument operating on this principle was constructed during the spring and summer of 1932. It underwent its preliminary tests during the fall of 1932, and has been in regular operation with only insignificant alterations since January, 1933.

This new spectrophotometer was described[6] before the Optical Society of America at a meeting held in February, 1934. In brief, the optical system of this instrument causes the light from an incandescent lamp to pass first through a double monochromator. The light in one narrow spectral region then enters the photometer unit consisting of two polarizing prisms with a Wollaston prism between them. The Wollaston prism divides the beam traversing it into two beams which are polarized in mutually perpendicular planes. One of these beams illuminates the test sample and the other illuminates the standard.[7] The second polarizing prism, which rotates about its axis at the rate of thirty revolutions per second, produces the required alternation of the two beams. The relative intensity of the two beams is controlled by the angular setting of the first polarizing prism with respect to the Wollaston prism. This setting is effected by a motor which is controlled in much the same manner as in the first instrument. Although it is possible to compute spectrophotometric data from the angular setting of the first polarizing prism, special cams have been provided which record the data either on a linear scale, a logarithmic scale, or on other scales that may be convenient in the solution of special problems.

During the summer of 1933, the General Electric Company undertook the construction of a commercial instrument embodying the optical parts of our new instrument. The first instrument of the new type was delivered to the Research Laboratories of the International Printing Ink Corporation, now a subsidiary of the Interchemical Corporation. The results obtained with this instrument were very satisfactory, and, although more than a score of these instruments have since been constructed, only minor alterations have been made in the design. One of these instruments has been recently purchased by the Electrical Testing Laboratories. The construction of the General Electric spectrophotometer is described in detail by Mr. Michaelson in the next paper.

The instrument which we placed in operation in January, 1933, has been used so constantly that many of the mechanical parts are beginning to show signs of wear. If we had anticipated that the instrument would often be called upon to make as many as three thousand spectrophotometric determinations in a single month, we might have made greater use of ball-bearings and might at least have provided for an adequate film of oil on the surfaces that are most likely to wear. Because of the undesirability of taking the instrument out of service long enough to replace the worn parts, we started the construction of a new instrument a little more than two years ago. This instrument, with the exception of two lenses which have been achromatized, employs an optical system which is identical with that of the previous model. Its mechanical construction is much more rugged and its electrical circuits more thoroughly shielded. By operating at 50 cycles, instead of at 60 cycles as in

[5] It may be fair to add that the precision of the instrument was enormous when compared with the precision of spectrophotometric estimates made by the unaided human eye.

[6] J. Opt. Soc. Am. **25**, 305 (1935).

[7] The light reflected alternately from the test sample and standard is depolarized before impinging on the photoelectric cell.

the previous instrument, greater freedom from the effect of stray currents present in our laboratory has been obtained. An automatic speed control on the wave-length drive has been added which causes the recording platen to move rapidly when the slope of the curve is nearly horizontal, and to decrease its speed as the slope of the curve increases. In addition, an electrical damping device has been provided which prevents the balancing system from hunting. The integrating attachment, mentioned in the publication referred to previously, has been built into the new instrument. This instrument has been undergoing tests for some time, and is expected to supplant the old instrument during the summer of 1938.

The pronoun *we* has been used throughout this discussion in the noneditorial sense. It is a pleasure to have the opportunity to acknowledge the aid received from several junior members of our staff who have contributed at various times to the advancement of the project. Special mention should be made of the assistance of Dr. Fred H. Perrin and Dr. F. W. Cunningham during the construction of the first model. Mr. O. W. Pineo and Dr. David Luck took part in the design and construction of the 1932 model. The instrument which is about to be placed in service is largely the result of the efforts of Mr. Ernst A. Nordberg, Dr. David L. MacAdam, and Dr. Ormond Barstow. There are many others whose contributions, although less extensive, are none the less appreciated, and I take this occasion to acknowledge their aid.

Construction of the General Electric Recording Spectrophotometer*

J. L. MICHAELSON
General Electric Company, Schenectady, New York
(Received July 5, 1938)

THE purpose of this paper is to discuss some of the problems and their solutions encountered in producing a commercial recording spectrophotometer after Hardy.[1] Professor Hardy's optical design as shown schematically in Fig. 1 dictated to a considerable extent the final mechanical form of this apparatus. Because of the large size of the complete instrument, it was thought advisable to divide it into two sections, namely, (1) the photometer, and (2) the monochromator and recorder. One advantage resulting from this division was to make both the photometer and the monochromator separately available for other applications, for which some have been found. Likewise, the difficulties in shipment were lessened. Fig. 2 shows the general arrangement of parts. They are supported on a $\frac{1}{4}$-inch panel which is in turn bolted to a welded steel frame-work which has been ground to a flat surface. This frame-work furnishes a suitable housing structure for the voltage amplifier and power stage. The construction is such that the photometer is a rigid unit in itself and entirely satisfactory for the job it is intended to do. Some care is necessary in setting up the monochromator in order that the wave-length scale may not be distorted. Once set up, however, this scale has been found to be quite satisfactory in regard to maintenance.

While the optical design dictated to a large extent the over-all size and to some extent the shape of the spectrophotometer, there was, however, considerable flexibility possible in the design of various component parts, and I will discuss these in more detail.

METHOD OF RECORDING

It was felt by all concerned that the record obtained should be an ink recording on a standard-size letter paper. Due to experience obtained with the first model of the recording photoelectric color analyzer[2] it was deemed advisable to make the longer scale photometric and

* Invited paper presented at the seventh annual meeting of the Inter-Society Color Council held at the Electrical Testing Laboratories, New York, February 24, 1938.

[1] J. Opt. Soc. Am. **25**, 305 (1935).

[2] A. C. Hardy, J. Opt. Soc. Am. and Rev. Sci. Inst. **18**, 96 (1929).

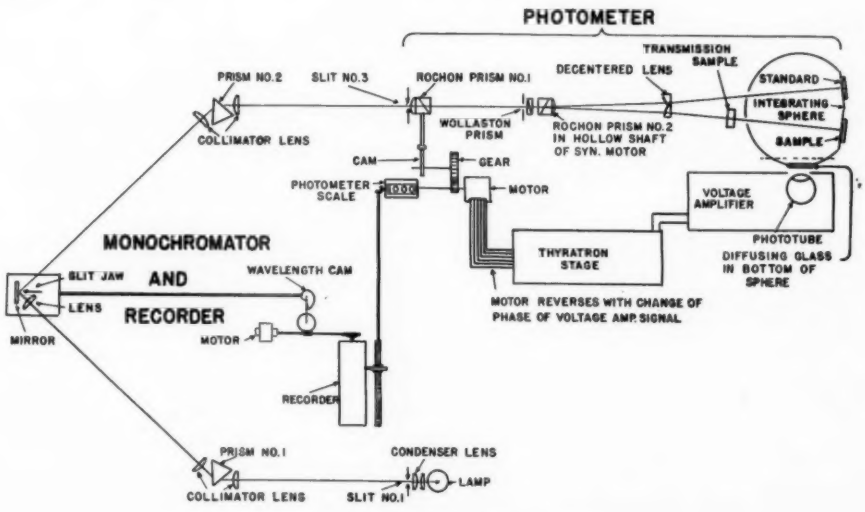

FIG. 1. Schematic diagram.

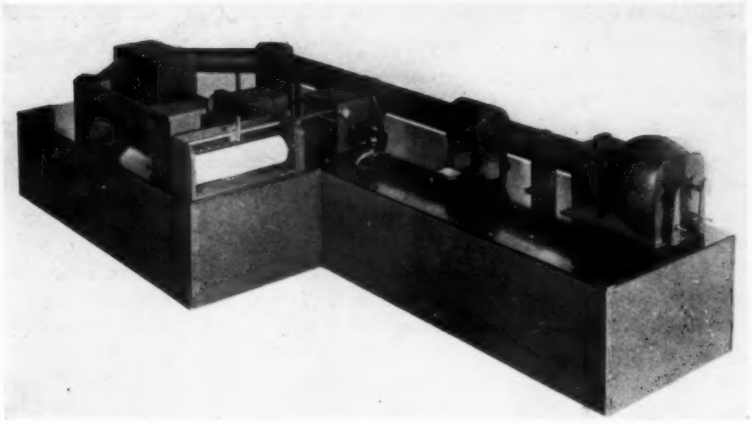

FIG. 2. Recording photoelectric spectrophotometer.

the shorter scale wave-length. Professor Hardy's original working sample of the recorder was a flat type in which the whole record was visible during the total operation. The disadvantage of the flat type recorder, however, was that it required considerably more space, and in general it was more complicated to attach to the spectrophotometer mechanism. Furthermore, it was felt that the advantage of seeing the whole record was largely a psychological one and in continuous use would not be important.

A close-up view of the recorder finally adopted is shown in Fig. 3. The photometric scale is 10 inches long and the chart paper used is divided into ½-percent divisions. The recording pen is an ordinary stylus type of fountain pen and is carried along the photometric scale by means of a screw. The wave-length scale of the chart occupies 300 degrees of the total 360 degrees of rotation, or 1 degree per millimicron in the standard instrument. The chart paper is cut parallel to the top horizontal line of the chart and the 700 mμ line is extended to the edge of the paper both at the top and at the bottom. This serves to line up the wave-length scale and also to make a quick check upon the accuracy of the cutting of the top edge of the paper.

WAVE-LENGTH MECHANISM

The wave-length motions required are movement of a reflecting mirror, movement of a slit jaw in front of this mirror, and movement of the bilateral slits, Nos. 1 and 3. The wave-length cam box, Fig. 4, shows the three cams and one gear which accomplish the above motions. The lower cam moves the wave-length mirror by means of a push rod. Through a push rod the cam for slit No. 2 controls the distance between the slit jaw and the wave-length mirror, compensating for the nonuniform dispersion of the prism. Likewise, the cam for slits 1 and 3 automatically adjusts the widths of these bilateral slits. A wave-length band of constant width is thus maintained. A wave-length scale is attached to this cam shaft which results in a minimum of mechanical linkage between the scale and the wave-length controlling cam. The active face of the cam is 300 degrees, corresponding to 1 degree per millimicron. The cams for slits 1 and 3 and for slit 2 are arranged on a sleeve such that other cams may be mounted on this same sleeve; a simple adjustment of the cams will thus change the width of the wave-length band passed by the monochromator.

The data for the cutting of these cams are obtained experimentally after the monochromator has been set up and adjusted. Mercury, helium, hydrogen and neon lines are employed to obtain data for the wave-length cam. The cam dimensions are given to the shop for every degree of rotation and to 1/10,000 of an inch radius. The slope of the wave-length cam at 700 mμ is ap-

proximately 0.002 inch per millimicron, and in the violet part of the spectrum is approximately 0.012 inch per millimicron. The worm-gear is driven by a motor through a worm which is on the same shaft as the worm driving the recorder drum. Thus the mechanical linkage between the recorder drum and the wave-length cam permits very little back-lash. Two recording speeds are available by means of a simple gear-shifting device.

The wave-length and slit mechanism shown in Fig. 5 is constructed as follows: The lower push-rod which comes from the cam compartment is attached to a table which is arranged to roll on three steel balls in such a manner as to obtain a three-point suspension. The push-rod from the cam for slit 2 moves a second table which likewise rolls on three steel balls arranged in grooves. The cam rods are held against the cam by means of springs concealed in the wave-length mechanism. This forms a very satisfactory movement in a device not intended to be portable. The wave-length mirror is a first-surface aluminized

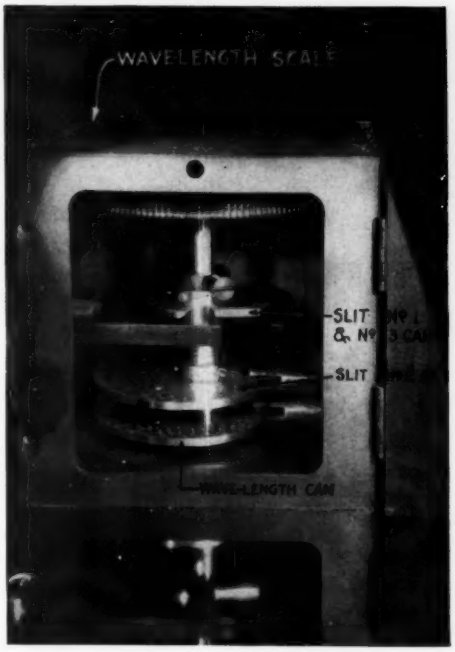

FIG. 4. Wave-length cam box.

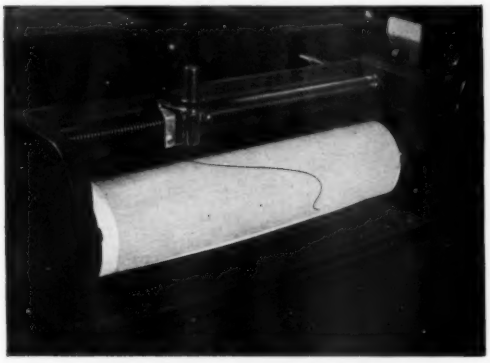

FIG. 3. G. E. recording spectrophotometer. Close-up view of record being made on chart.

mirror. The effective lengths of the cam push-rods are adjustable. The approximate distance between the slit jaw and the mirror surface is 0.010 inch at 700 mμ and 0.062 inch at 400 mμ.

CONSTRUCTION OF SLITS NOS. 1 AND 3

Slits 1 and 3 are identical in construction and consist primarily of two slit jaws which are moved by means of a centrally located cam, as shown in Fig. 6. These slits are driven by means of a gear and pinion which in turn is attached to push-rods operating from the cam for slits 1 and 3 of the wave-length mechanism. Slit 1 is usually operated 50 percent wider than slit 3 in order that the monochromator may be filled with light at all times. Slit 3 is straight, as the curvature of the spectrum does not introduce appreciable error for a 10-millimicron band. When a smaller wave-length band is required it is necessary to make slit 3 slightly curved.

MOUNTING FOR THE ANALYZING PRISM

Figure 7 shows the rochon analyzing prism. This prism is required to rotate through a total of 45 degrees corresponding to 0 and 100 percent transmission or reflectance. It is mounted in a composition holder and is rotated in a double-roll ball bearing which, of course, maintains very good alignment. The photometer cam rider is coupled to the rochon-prism holder through a thin band of phosphor bronze. As a result we obtain an angular motion which is strictly pro-

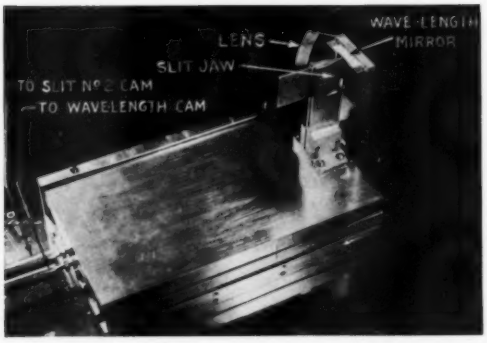

FIG. 5. Wave-length and slit mechanism.

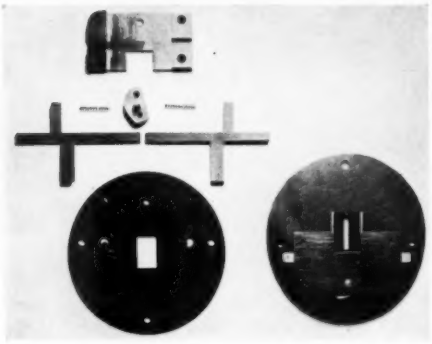

FIG. 6. Disassembled slit mechanism for G. E. recording spectrophotometer.

portional to the displacement of the cam rider. The effective length of this phosphor bronze strip is adjustable. It is held under tension by means of a spiral spring on the prism holder. The photometer cams are cut from the tangent-square formula to an accuracy of ± 0.0004 inch. At the point of lowest slope, 0.005 inch corresponds to 1 percent of the photometer scale. The photometer cams on all of the instruments are alike; that is, there has been no change on the photometer cam to compensate for photometric errors discovered in testing. Near the zero part of the cam (larger radii) the slope of the tangent-square curve becomes infinite and, of course, the cam rod will not follow this slope. Therefore, it is necessary to deviate from the tangent-square law near zero, which, of course, introduces an error in the photometric scale. This deviation occurs below 1 percent, which is of no importance in reflection measurements on this instrument. The true zero occurs several degrees below the mathematical zero on the cam. A micro-switch has been used to open the thyratron circuit which drives the balance holder down scale when the indicator reads zero. Thus a perfectly opaque transmission sample will

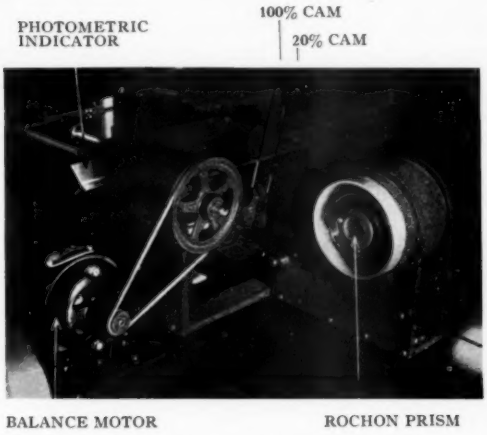

FIG. 7. Mounting for the analyzing prism.

FIG. 8. Flicker motor and Wollaston-prism holder.

measure zero as will a sample transmitting 3/10 of 1 percent. On the 20 percent scale the 20 percent cam is accurate at the 0 end to approximately 0.1 percent. The 100 percent and 20 percent cams are mounted on a sleeve which allows the convenient substitution of one cam for the other. It is possible to add other cams to this sleeve, such as log and log log cams. The flexibility of the design makes it possible to obtain nearly any sort of photometric scale which may be desired.

Flicker Motor and Wollaston-Prism Holder

Figure 8 shows the Wollaston-prism holder mounted on the end of the synchronous flicker motor which is used to rotate the flicker rochon prism. This motor consists of a wound rotor with a hollow shaft. The stator is wound with polarizing coils in order to make it start in the same phase position each time. The temperature rise in this motor is kept low by operating it at the minimum voltage which will maintain it in synchronism. The stator has an angular adjustment which is necessary to get the correct phase relation between the signal and the power.

Integrating Sphere

The integrating sphere consists of an 8-inch spun sphere with three plane sections inserted.

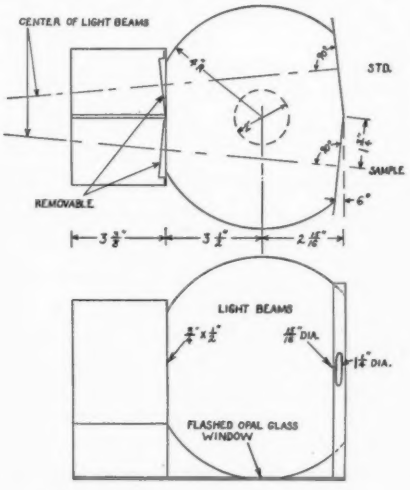

Fig. 9. Geometry of integrating sphere.

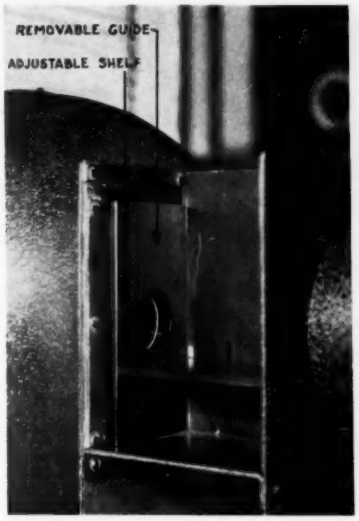

Fig. 10. Transmission compartment of the sphere.

One is at the transmission position and one each at the sample and standard positions. See Fig. 9. The light is incident normally on the sample and standard and illuminates a portion approximately 1 inch in diameter. The inner wall of the sphere is coated with a special mat white paint and later smoked with magnesium oxide. Fig. 10 shows the transmission compartment of the sphere. It is possible to obtain diffuse transmission measurements by removing the guide and placing the sample in contact with the sphere wall. When specular transmission measurements are desired, the guides serve for alignment of the sample.

Voltage Amplifier

Figure 11 shows the voltage amplifier with the top cover removed. The PJ-15 phototube lies directly under the opal glass window in the bottom of the integrating sphere. The phototube and first stage amplifier are located in one compartment of this amplifier which is maintained dry by means of a heating coil when the instrument is not in use. There is no grid leak employed in this phototube first-stage circuit. The d.c. impedance is of the order of 10,000 megohms. Since the grid impedance of the amplifier tube is the phototube load, it is necessary to obtain

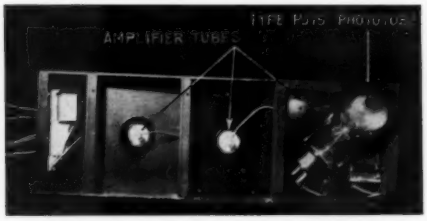

FIG. 11. Voltage amplifier and phototube.

some degree of matching in characteristics between the phototube and the amplifier tube. This match is obtained by a preselection of the amplifier and phototube and also by an adjustment of the screen-grid voltage of the first-stage amplifier. The filament, plate and screen-grid voltages of this first-stage amplifier are operated below normal voltage to insure long life and stable operation of this circuit. Amplifiers of this design have now been operating several years without appreciable change in characteristics. The amount of radiant energy reaching the phototube at normal operation is extremely small and this constituted the major difficulty in obtaining a practical commercial instrument. The normal phototube current at 400 mμ is approximately 10^{-12} ampere for a 100 percent sample. Since we desire a sensitivity of better than 1/10 of 1 percent it is necessary to detect a phototube current of the order of 10^{-15} ampere. This roughly corresponds to a phototube illumination such as would be obtained from a candle one mile away. This is further complicated by the fact that the noise level of the photo-cell is about the same order of magnitude as the above signal. The total voltage gain of the amplifier is in the neighborhood of 100,000.

The whole amplifier is supported as a unit on rubber mountings in order to isolate it mechanically from the rest of the instrument. This is necessary to keep microphonic disturbances out of the amplifier signal. Fig. 12 shows a schematic diagram of the power stage which consists primarily of two thyratrons, a reactor, and a power transformer. The thyratrons are arranged with their plates in push-pull arrangement and their grids in parallel. The amplifier voltage is 60 cycle a.c. and is in phase with the 60-cycle voltage of the transformer winding. Under these conditions one of the thyratrons passes current giving a resultant current flow in $\frac{1}{2}$ the field and in the armature of the balance motor corresponding to a particular direction of rotation. When the voltage-amplifier signal is 180 degrees out of phase with the power on the transformer, the opposite thyratron passes current and consequently the armature and the other half of the field of the balance motor is excited and the motor runs in the reverse direction. Thus the direction of rotation of the balance motor depends only upon the phase of the voltage amplifier signal; it is always in such a direction as to correct the out of balance condition existing at that moment in the photometer system.

In the discussion following the paper Dr. R. H. Osborne, Hercules Powder Company, inquired as to the cause of the jiggling of the pen and balance motor. In reply, it was stated that there might be several causes. If a pure a.c. signal came out of the voltage amplifier, there would be a serious problem of "hunting." Because of the inertia of the balance system, there would be oscillations about the true balance position. However, the signal is contaminated with considerable phototube noise, the effect of which is critically to damp the system. Sometimes a change in the ratio of noise to signal will cause the jiggling, and this can usually be corrected by changing the size of the capacitor across the input reactor of the power stage.

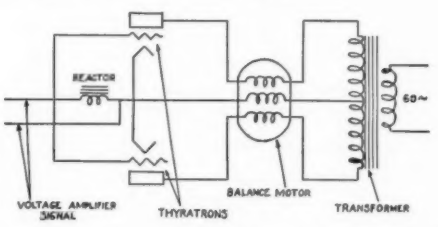

FIG. 12. Schematic diagram of power stage for spectrophotometer.

Dr. A. W. Kenney, duPont Company, inquired as to the life to be expected of the General Electric instruments. In reply, it was stated that on one instrument in Schenectady approximately 3000 curves had been made in 1937 and 2000 in 1936, and no deterioration of the instrument had been detected.

Dr. Osborne also inquired as to the best ink to use in the pen for photographic reproduction,

stating that most recording inks were not opaque enough for good reproduction. He had found the ink designated as Eastman Opaque to be the best in this respect, although it clogged the pen. Chairman Dimmick mentioned the ink used by the Taylor Instrument Company for their recorders; he had found it satisfactory for recording but was uncertain as to the photographic reproduction. The author stated that he had found Skrip's black fountain-pen ink quite satisfactory; that it photographed well and wrote well.

Dr. R. Sawyer, Krebs Pigment and Color Corporation, asked if there were any data on comparisons or cross checks of the General Electric spectrophotometers. In reply, it was stated that all of these instruments are checked by means of a group of five glass filters whose spectral transmissions were originally measured at the National Bureau of Standards, and that in general the values obtained in the various instruments have differed by no more than the uncertainties given for the respective values in the Bureau report.

Calibration and Operation of the General Electric Recording Spectrophotometer of the National Bureau of Standards*†

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(Received July 5, 1938)

I. INTRODUCTION

THE General Electric recording spectrophotometer installed at the National Bureau of Standards has certain features not found on the regular commercial form of this instrument. These are:

(1) The wave-length scale covers the range from 400 to 750 mμ. The extension of the scale, from the usual limit at 700 mμ to 750 mμ, was needed particularly because of the Bureau's extensive work on signal glasses. The illuminant for such glasses is usually an incandescent lamp or kerosene flame, and the region above 700 mμ is of considerable importance in the computation of the luminous transmission of certain of these glasses for such illuminants. Furthermore, the I.C.I. standard observer and coordinate system are defined by numbers covering the spectral range from 380 to 770 mμ; extrapolation from 700 to 770 mμ seemed undesirably large, even though the usual colorimetric computational methods give but little weight to values in this range.

(2) Instead of the usual 10-mμ slits, the Bureau instrument has cams enabling slits approximately 4 or 8 mμ in width to be used. The narrower the slits the more accurate is the spectrophotometric analysis obtainable. The disadvantage of the smaller slit-width is the increased difficulty of operation resulting from the decreased ratio of signal to "noise."

(3) In addition to the normal and the ×5 cam, the instrument has cams which plot the transmission or reflection curves on a log scale or on a log log scale. These latter are of use in the study of solutions and dyed fabrics.

(4) Shortly after installation of the instrument it was found that improved operation was obtainable by use of a series of voltages above the 22½ volts regularly applied to the screen grid of the second and third amplifier tubes and to the plate of the first tube.[1]

(5) Improved operation was further secured by installation of variable capacity in the output impedance of the amplifier (input impedance of the thyratrons). Capacities from 0.0005 to 0.0065 microfarad by steps of 0.0005 microfarad were installed; these, together with the variable screen-grid voltages (at present from 18 to 31½ volts by steps of 1½ volts), enable us to operate the instrument continuously under conditions of optimum sensitivity.[2]

(6) The recording pen which came with the instrument has been replaced with another pen giving a finer line. This has proved of advantage in reading values from the curves, especially from two nearly identical curves on the same sheet. All the curves shown in this paper were obtained with this finer pen.

II. QUANTITIES MEASURED

It is well to recall just what is measured on a spectrophotometer. In all spectral reflection measurements of diffusing samples, the quantity measured is the apparent reflectance[3] relative to

* Invited paper presented at the seventh annual meeting of the Inter-Society Color Council held at the Electrical Testing Laboratories, New York, February 24, 1938.

† Publication approved by the Director of the National Bureau of Standards of the U. S. Department of Commerce.

[1] The authors are pleased to acknowledge the advice and assistance of Mr. E. G. Lapham of the Bureau's radio section in connection with their study of the electrical parts of the instrument.

[2] The variable capacity was suggested by Mr. Michaelson of the General Electric Company to whom the authors are greatly indebted for the care with which the instrument was installed and tested, not only at the original installation but upon the occasion of a return visit about a year later.

[3] Measurements of absolute reflectance are, of course, possible with specially designed equipment and such measurements have often been made as a function of wavelength in the case of polished metal surfaces. Commercial spectrophotometers are not designed primarily for such measurements; an approximation to absolute reflectance values may be obtained on the G. E. instrument, however, if (1) the MgO comparison surface is fresh, (2) the interior of the sphere is uniformly coated with MgO, and (3) the polished surface is inclined so that all the specularly reflected light is directed into the sphere, as was done in Fig. 4.

MgO (or other standard used), for the particular conditions of irradiation and "viewing" pertaining to that instrument. On the G.E. instrument the irradiation of the sample and reference standard is approximately at right angles to their surfaces and the reflected energy is taken in all directions except that from which the incident energy comes. The so-called specular component of the reflected energy is, therefore, partially eliminated from the measurements by escape through the entrance apertures; this elimination is not complete, however, because of spread in the beams. For glossy samples the values obtained deviate importantly from those which would be obtained if the instrument design were such as to include or exclude this component completely. For example, a piece of polished black glass, which for normal incidence, should reflect about 4 percent of the visible radiant energy if the specular component be included in the measurements, and should appear to have zero reflectance if this component be totally excluded, gives an intermediate value of about 2.6 percent on the Bureau instrument. For nearly mat samples the values obtained are not importantly affected by such differences in the conditions of measurement.

By the Helmholtz reciprocity law,[4] the value of apparent reflectance obtained under the conditions of irradiation and reflection used on this instrument is numerically equal to that which would be obtained if (1) the sample and standard were irradiated diffusely, except from that part of the subtended hemisphere now occupied by the entrance apertures, and (2) the reflected energy were taken at approximately right angles to the surfaces.

Differing from the usual design of spectrophotometer for transmission measurements, the G.E. instrument includes in the measurement a considerable amount of the energy scattered by the sample. The design of the Bureau instrument is such that the sample is normally placed at right angles to the beam and with its closest surface about 1 cm from the sphere opening, the resulting used aperture of the transmitted light being about $\frac{1}{2}$ of the total subtended hemisphere. However, most of the energy transmitted by a diffusing sample can be measured, if desired, by removing the supporting diaphragm and placing the sample directly against the sphere. For nondiffusing samples the results would, of course, be identical with the usual rectilinear-transmission measurements. Any diffusion of the energy by the sample causes a transmission to be obtained which is greater than would be obtained on an instrument measuring only the energy transmitted in a direction approximately at right angles to the surfaces of the sample. Of course, if the sample is measured relative to a similar reference standard in the other beam (for example, solution in cell relative to solvent in cell), this difference tends to disappear.

[4] H. J. McNicholas, Nat. Bur. Stand. J. Research **1**, 29 (1928) RP 3.

III. Calibration Curves

In general, each sheet run on the Bureau instrument has three calibration curves placed upon it. These are illustrated in Fig. 1.

1. The zero curve

With the cam and indicator at the proper positions, test is made after the insertion of each sheet to see if the pen is recording properly on the zero line. If not, the position of the pen is adjusted (without changing the position of the cam or the reading of the indicator) until the pen does record accurately on the zero line near 550 mμ. When so adjusted, the zero curve (sample beam completely blocked off) on the Bureau instrument is slightly high at 400 mμ and slightly low at 750 mμ, the extreme deviations being usually about $+0.1_5$ and -0.1_5 percent, respectively. This is apparently due to distortion of the cross section network of lines on the paper. The 100 percent coordinate line is quite accurately parallel to the top edge of the paper, but progressively as the zero coordinate line is approached the left side of the network is distorted downward relative to the right side, and by practically the correct amount to explain the slope of the recorded zero curve.

In the discussion following this paper, Mr. O. W. Pineo, Calco Chemical Company, raised the question as to the proper method of making the zero calibration. The present discussion extends that given at the meeting. On the Bureau instru-

ment, the situation is as follows: In the operating instructions accompanying the instrument it is stated, "From 0.5 percent to 0.0 percent, the tangent square curve is too steep for a cam rod to follow. Thus, the cam shape is not tangent square in this region. A curve showing the cam error for this range is attached." The values in Table I are as read from this curve.

As explained in Mr. Michaelson's paper, an electrical stop prevents the cam and indicator from going below the reading 0000, and at this reading the true photometric value (for example, the spectral transmission) may on the Bureau instrument be anywhere from 0.24 percent to 0.00 percent. The true test of the extinction position is to force the cam and indicator past 0000 to about 9992 and see if the comparison beam is then extinct. If not, the first rochon and the Wollaston prisms are not in correct relative position.

However, if the relative positions of the Wollaston and analyzing prisms are disturbed from their correct positions, this will be shown, on the normal cam, far more sensitively by the displacement of the 100 percent curve than by any observable displacement of the extinction position. Since the measured quantity, for example the percent transmission T, is proportional to the $\tan^2$ of the angle through which the analyzing prism turns from extinction (0°) to balance (45°), we have as the equation on the basis of which the normal cam is cut:

$$T = 100 \tan^2 \alpha,$$

from which

$$\Delta T \doteq 100(2 \tan \alpha/\cos^2 \alpha)\Delta\alpha$$
$$\doteq 0.0175 \times 100(2 \tan \alpha/\cos^2 \alpha)\Delta\alpha,$$

when $\Delta\alpha$ is expressed in degrees.

From this it is seen that $\Delta T/\Delta\alpha$ is zero at $\alpha = 0°$, increasing continuously up to and beyond $\alpha = 45°$. If $\Delta\alpha$ be taken as 1°, ΔT will be about 7.0 when $T = 100$ ($\alpha = 45°$), but less than 0.3 when $T = 0.5$ ($\alpha = 4°$). On the normal cam one therefore need not worry much about the correct extinction reading so long as the 100 percent adjustment is approximately correct. This in fact is the justification for the method used to make the 100 percent adjustment; one can adjust the 100 percent dial reading and curve by small amounts

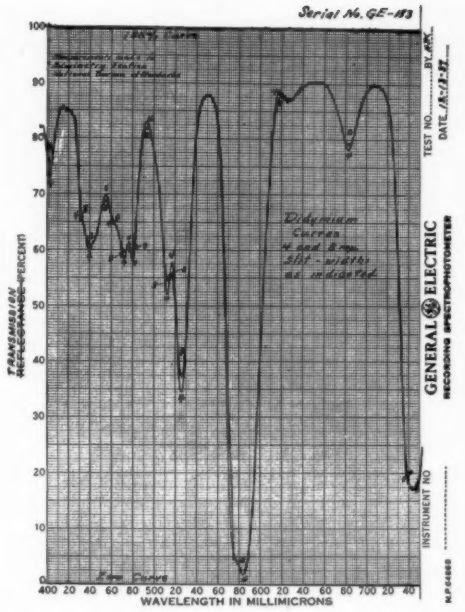

FIG. 1. Illustrating the calibration curves usually run on the Bureau instrument. Note also the effect of slit-width on the transmission curve of the didymium glass. This and the following figures are reproductions of the actual recordings as made on the instrument.

without importantly affecting the extinction position. An occasional examination of the extinction position is therefore sufficient, but one should adjust the position of the pen, if necessary, on each sheet at the zero line to avoid displacement of the whole sheet of curves.

However, with the log cam the situation is reversed. In this case

$$-\log_{10}(T/100) = D = -\log_{10} \tan^2 \alpha$$

and

$$\Delta D \doteq (-\log_{10} e/\tan^2 \alpha) \cdot (2 \tan \alpha/\cos^2 \alpha)\Delta\alpha$$
$$\doteq (-4 \log_{10} e/\sin 2\alpha)\Delta\alpha.$$

$\Delta D/\Delta\alpha$ is a maximum at $\alpha = 0°$ and decreases continuously up to $\alpha = 45°$. If $\Delta\alpha$ be again taken as 1°, $\Delta D = -0.03$ when $\alpha = 45°$ and equals -0.2 when $\alpha = 4°$. The authors have not had occasion to use this cam much, but apparently one should have available a standard whose transmission is accurately known at some low transmission (for example, $T = 1.0$ percent, $D = 2.0$) and be sure that the adjustment is such as to give this value accurately. On the Bureau instrument, the D scale

extends from 0 to 3, corresponding to $\tan^2 \alpha$ from 1.00 to 0.001.

On the log log cam we have

$$S = +\log_{10} D = +\log_{10} (-\log_{10} \tan^2 \alpha).$$

$$\Delta S \doteq (+\log_{10} e/D)\Delta D$$

$$\doteq \frac{4(\log_{10} e)^2}{(\log_{10} \tan^2 \alpha) \sin 2\alpha} \Delta\alpha.$$

This shows $\Delta S/\Delta\alpha$ to be very large for α close to 0° or 45°. The cam is cut to cover values of $\tan^2 \alpha$ from 0.99 to 0.001. In this case, one can plot neither a zero nor a 100 percent curve, and a check on a standard of known transmission is desirable.

2. The 100 percent curve

In the case of transmission measurements the 100 percent curve is that obtained either with no sample in the beams, as illustrated in Fig. 1, or with identical materials in each beam, for example, absorption cells filled with solvent only. In such cases, it makes no difference what materials are used for the reflecting surfaces or whether they are identical, except that (1) they should be diffusing and of high reflectance in order not to lose sensibility and (2) they must be nearly identical[5] if the 100 percent curve is to lie close to the 100 percent coordinate line, the instrument being in proper adjustment. This close agreement of the 100 percent curve and coordinate line is, of course, important if the discrepancy is to be ignored, and it is a matter of convenience in reading and computing if corrections are to be made.

TABLE I

PHOTOMETRIC INDICATOR (DIAL)	PHOTOMETRIC VALUE (TRUE)
0007	0.70%
0006	.60
0005	.52
0004	.45
0003	.39
0002	.33
0001	.28
0000	.24
9999	.20
9996	.10
9992+	.00

[5] The identity of two samples can be tested by making two measurements with the samples interchanged between the measurements. Identical samples will give identical curves.

In reflection measurements the same close agreement between the 100 percent curve and coordinate line is desirable as a matter of convenience, but the situation is otherwise different. It is now important what material is used as the reference standard on the sample side in obtaining the 100 percent curve, regardless of whether or not the same material is used on the comparison side. It must be remembered that a reflection curve is always obtained relative to the material used on the sample side in obtaining the 100 percent curve. To date, the most suitable reflection standard available appears to be a freshly prepared layer of magnesium oxide, MgO. This is considered further below.

3. The didymium glass curve for wave-length calibration

The transmission curves of a certain piece of Jena didymium glass (BG 11, 8.17 mm) are shown in Fig. 1; these were obtained with slit-widths of approximately 4 and 8 mμ, as noted. These curves illustrate the effect of different slit-widths on a curve of this kind. With most materials, however, the slit-width effect is much less marked than here shown. It is worth noting that the effect is greatest where the curvature is greatest, that is, around the peaks of the sharpest absorption or transmission bands, and that it is zero or negligible on the steep parts of the curves in the neighborhood of the inflection points. This is in agreement with the theories of slit-width correction, which show that the errors or corrections are dependent on the second, but not the first, derivative of the resulting distribution curve.[6]

It may be noted that with the 4-mμ slits there are eight absorption bands useful for wave-length calibration. These are located at 402.2, 440.1, (472, not used) 479.9, 513.3, 527.5, 584.7, 683.9, 744.0 mμ.[7] To supplement these values in the larger intervals, use has also been made of the transmission band located at 617.9 mμ, and

[6] The difference in the two curves in the region of 570 mμ is not a slit-width effect. The upper curve has lagged; this is due to a certain "blocking effect" often caused on this very steep curve if the screen-grid voltage is too high. No such blocking occurred, for example, in the didymium curves of Figs. 2 and 3.

[7] The authors are pleased to acknowledge the assistance of Mrs. G. W. Haupt in the determination of these values, also in certain of the values given in Tables II and III, below.

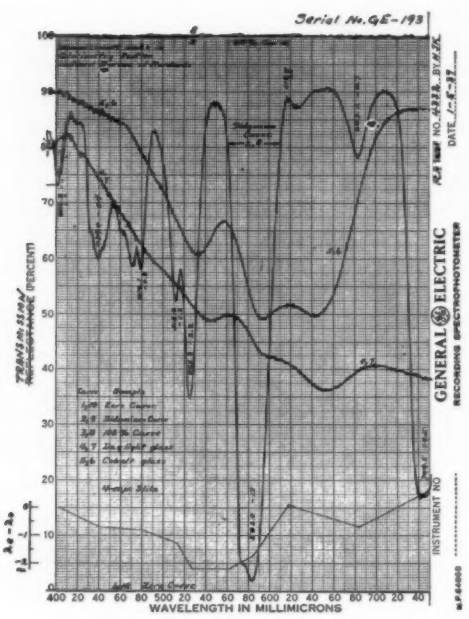

FIG. 2. Typical curves obtained with 4-mμ slits.

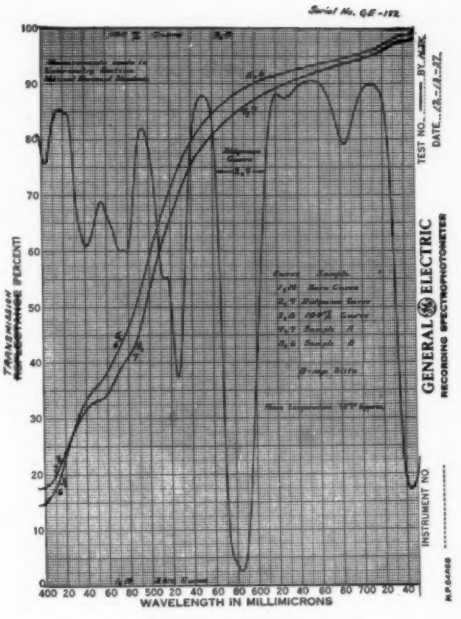

FIG. 3. Typical curves obtained with 8-mμ slits.

of a special filter[8] with sharp transmission band at 561 mμ. The wave-lengths stated for the bands of the didymium glass and the special filter were determined by careful measurement on other spectrophotometers and have an uncertainty considered not greater than 0.2 or 0.3 mμ. The method of making the wave-length correction is considered below.[9]

IV. Precision and Reproducibility

Before considering the application of these calibration curves and other factors affecting the accuracy of measurement, it is desired to illustrate the reproducibility of the Bureau instrument both during the past few months and as it was a year or so ago. In Figs. 2 and 3 are shown fairly representative sheets recently obtained with 4 and 8 mμ slits, respectively. Each of the curves in both figures has been traced twice, the numbers on the curves indicating the order in which they were taken.[10] Two things may be noted: (1) The curves with the 4-mμ slits are considerably less smooth than those with the 8-mμ slits. This is due to the decreased ratio of signal to "noise" with the 4-mμ slits. (2) There is excellent reproducibility in all the curves. This is, of course, one of the outstanding features of this instrument and method, and the large saving in time resulting from its use in spectrophotometric analysis and identification compared to manually operated instruments is obvious.

The precision and reproducibility illustrated in Figs. 2 and 3, were not, however, in general obtainable throughout the first year of operation of the instrument. At first a considerable sluggishness often occurred resulting in serious lag, so much so that at times the instrument could not be used for the desired measurements. This was apparently due largely to the use of 4-mμ slits on an instrument whose electrical and optical parts were designed primarily on the basis of 10-mμ slits. This sluggishness was remedied, as already noted, by the introduction

[8] Kasson S. Gibson, Nat. Bur. Stand. J. Research **14**, 545 (1935) RP 785; also J. Opt. Soc. Am. **25**, 131 (1935).

[9] A further check on the accuracy of the wave-length scale is to let the instrument plot a vertical line across the whole sheet, as has been recommended by Mr. Pineo. This line must be accurately parallel to the vertical lines of the network. One should be satisfied, by test or experience, that this condition is fulfilled on each sheet.

[10] The $\lambda_e - \lambda_t$ curve of Fig. 2 will be considered later.

of variable voltage and capacity at certain places in the circuits.

Other difficulties gradually developed, however, which are illustrated in Fig. 4. One of these was the failure of the 100 percent and didymium curves to repeat themselves at the end of a run; compare curves 2 and 11, and curves 3 and 9. The differences amounted to ½ to 1 percent depending on the length of time between the first and second curves in either case. The second difficulty was the selectivity which developed in the 100 percent curve, this becoming high in the violet and low in the red; this is illustrated in Figs. 4 and 8.

Both of these troubles were eventually traced to a slight blocking of the beams by the diaphragms over the decentered lenses. There was apparently a slight differential effect through the spectrum, causing the selectivity in the 100 percent curve. There was also apparently a second differential effect, varying with time; this was probably caused by expansion of certain parts of the instrument with slowly increasing temperature, affecting one beam more than the other. At any rate, slightly enlarging the diaphragm remedied both difficulties and resulted in the much superior curves illustrated in Figs. 2 and 3.

In discussion Dr. D. L. McAdam, Eastman Kodak Company, said that a curved 100 percent line had at first also been experienced on their instrument. In this case, the trouble was traced to a slight interception of the beams at the entrance apertures of the sphere. This was remedied by making the holes slightly larger and it was pointed out that one must look through the entire optical system in case of such trouble.

The proper operating speed of the instrument bears on both the reproducibility and the accuracy of the results. Dr. L. C. Lewis, Mead Corporation, has found that their instrument can be operated two or three times as fast as provided by the regular mechanism and inquired as to what was considered the limiting speed on the Bureau instrument. In reply, it was stated that the Bureau instrument has two speeds, 2½ and 5 minutes, approximately, and that the speed used depends on the type of curve, slow speed for those where the transmission or reflection is varying rapidly with wave-length, fast speed for the relatively nonselective curves. With 4-mμ slits one could not safely operate faster than the speeds provided on the instrument. The question can be answered with certainty only by test. If two speeds give identical curves, it is then safe to operate on the faster speed.

(Figure 4, incidentally, shows an interesting analysis of the light reflected from certain polished red, yellow, and green glasses backed by black velvet. When the samples are inclined slightly (about 10°) so that all the specularly reflected light is incident on the sphere wall (none escaping through the entrance aperture), we have the usual first surface reflection (approximately 4 percent) plus whatever returns through the glass from the second surface reflection. Clear glass, backed by black velvet, would thus reflect between 8 and 9 percent and the curves for the red, yellow, and green glasses are seen to lie between the 4 and 9 percent limits.)

V. Selectivity of Magnesium Oxide

So far as known at present, freshly prepared MgO affords the most satisfactory standard of

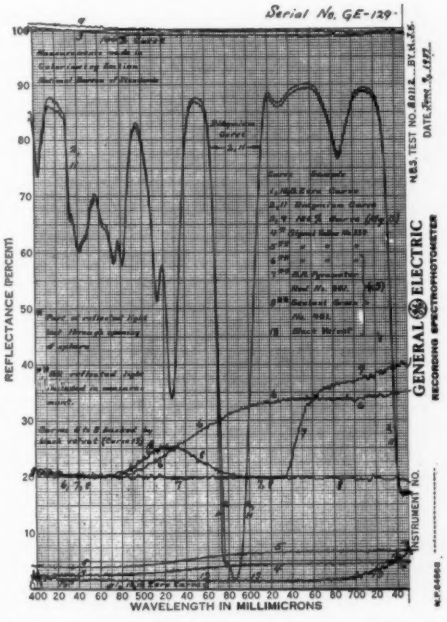

FIG. 4. Effect of beam obstruction on the selectivity of the 100 percent curve and on the reproducibility of the 100 percent and the didymium glass curves

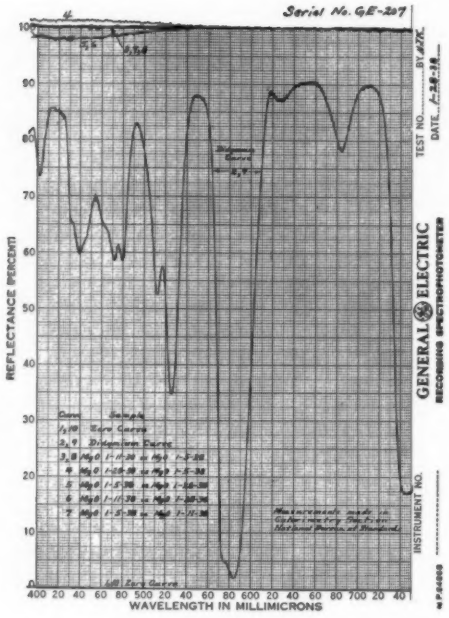
Serial No. GE-207
GENERAL ELECTRIC
RECORDING SPECTROPHOTOMETER
REFLECTANCE PERCENT
WAVELENGTH IN MILLIMICRONS
400 20 40 60 80 500 20 40 60 80 600 20 40 60 80 700 20 40

FIG. 5. Selectivity of MgO surfaces 2½ to 3½ weeks old compared to that of a freshly prepared MgO surface.

apparent reflectance available.[11] Its reflectance is high and almost nonselective and it is a good diffuser. It is likewise readily prepared. When properly prepared it is distinctly superior to $MgCO_3$ in that it is less selective (all samples of $MgCO_3$ examined have been yellowish) and more reproducible. It must be admitted, however, that the degree of reproducibility and the factors affecting such reproducibility have never been adequately studied. It is now established that MgO surfaces become slightly yellower with time, and this is illustrated in Fig. 5. Curves 5 and 6 show the reflectance of 23-day and 17-day old surfaces of MgO relative to a freshly prepared surface, and are representative of many similar tests that have been made on other MgO surfaces. The exact rate of this change and how it may be affected by preparation of the sample, by humidity, and by other factors is not yet known. The important thing to note, however, is that if one wishes to avoid errors of 1 to 3 percent of the value (perhaps even larger) in reflection measurements at the shorter wave-lengths, he must use freshly prepared MgO surfaces.

The MgO surfaces referred to in the previous paragraph are those obtained by deposition from burning magnesium. It is also possible to use commercial MgO in powdered form. It takes less time to prepare a reflectance standard from such material by pressing it into a mold. Such standards are now being regularly used in certain laboratories. The convenience of preparation warrants serious consideration of the use of such surfaces as standards, but no data have been published to illustrate how it compares with the smoked MgO surfaces.

Figure 5 illustrates another possible error which should be avoided. Curve 4 is the reverse of curves 5 and 6; that is, the samples have been interchanged. It will be noted that curve 4 does not extend as far above the 100 percent curve as curves 5 and 6 extend below. This lack of symmetry is noticeable where the true deviation from the 100 percent curve is greater than 1 percent. It means, of course, merely that no effort was made to maintain accuracy in the cam above the 101 percent value, and such accuracy should not be assumed if the 100 percent curve goes much above the 100 percent coordinate line.

VI. Wave-Length Calibration

The method of making the wave-length calibration of a sheet is illustrated in Fig. 6. Curves 1 and 7 are the usual didymium glass transmission curves run on practically all sheets with the Bureau instrument. Above each of the used bands are given the values, λ_e, of the wave-lengths of maximum absorption or transmission as read on this sheet. The vertical lines near these bands are plotted at the true wave-lengths, λ_t, as given above in Section III. Values of $\lambda_e - \lambda_t$ thus obtained are plotted as curve 200, to the improvised scale at the left of the sheet. They are seen to vary from -2.2 mμ at 527.5 mμ to $+0.5$ mμ at 744 mμ. The correction at 561 mμ has been found to equal that at 527.5 mμ. The shape of this correction curve shows that no position of the paper will eliminate the need for wave-length correction if the greatest accuracy of reading is desired, although the position of

[11] "Preparation and Colorimetric Properties of a Magnesium-Oxide Reflectance Standard," NBS Letter Circular, LC-395, 1936.

the paper (or pen) could have been adjusted so that the average values of $\lambda_e - \lambda_t$ for curve 200 would approximate zero instead of -1.0. A great advantage of this method of wave-length correction is, however, that both the errors in the cam and the errors of insertion of the sheet are eliminated, and one need not be too particular that the sheet is inserted in the best average position.

Another advantage of this method of wave-length calibration is that the instrument is automatically calibrated while in actual use, not at some previous time and with the instrument at rest. It also eliminates any day to day variation of the wave-length scale due to shrinkage or expansion of the paper or to any variation of the position of the beam on the exit slit. This latter effect can easily happen on the Bureau instrument as a result of warping of the wooden table on which the instrument is mounted. Curves 38 and 159 (taken from Fig. 8) show the variations in the shape of the $\lambda_e - \lambda_t$ curve that have occurred from time to time from these or other causes; see also the curve in Fig. 2. While differences between these correction curves of only a few tenths of one millimicron are not outside the uncertainties involved in reading the wave-lengths, the variation from curve 38 to curve 159 is undoubtedly real and of considerable importance for many types of transmission or reflection curves.

The importance of continuously checking the wave-length scale of the instrument was further emphasized by Dr. McAdam, who pointed out that the graph paper supplied with their instrument had been found to change in width by more than 2 millimicrons as a result of changes in humidity. He has found that one must check continually to make sure that the graph paper has not introduced erroneous results.

VII. Reduction of Data

It is believed that the procedure followed at the Bureau in reducing data from the tracings made on the G.E. spectrophotometer is of sufficient interest to note here. It should be pointed out, however, that in certain types of work it is unnecessary to take the time and trouble to record and use, for the reduction of data, correction curves such as are illustrated below. For example, in production work where the problem consists in duplicating a sample which is at hand, it may be necessary only to run the two curves to secure the desired information. Without the aid of spectrophotometry, the dyer may experiment for days or weeks before he obtains a color match that will hold under all ordinary types of illumination. Whereas, if the two spectrophotometric curves are identical or nearly so, he can be assured that the samples will match or closely match under all illuminants. Furthermore, where two curves are nearly identical and it is desired to compute the magnitude of the small color difference in terms of tristimulus values, it is likewise unimportant whether or not the correct colorimetric values of either curve are known. If the causes of the errors are the same for each curve and the errors themselves are not excessive, the computed colorimetric differences will be the same even though the curves themselves are in error.

The following is taken from a memorandum issued with blueprints of the tracings in all

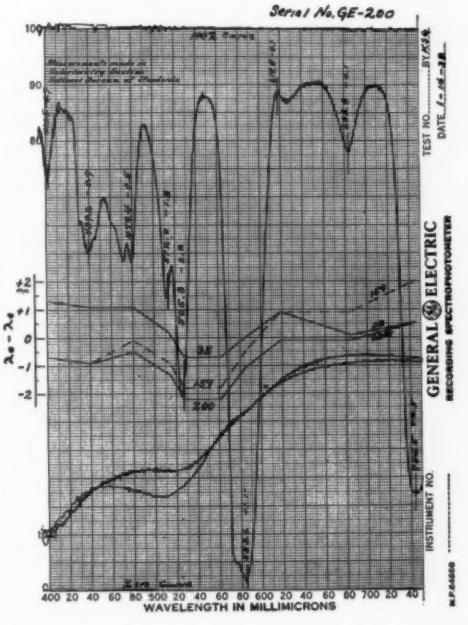

FIG. 6. Use of the didymium glass curve in wave-length calibration.

Bureau reports of tests made with this instrument:

"In reducing the data one should first correct for the wave-length errors. Designate the true wave-length by λ_t, the wave-length as read on the graph by λ_e. Plot values of $\lambda_e-\lambda_t$ as a function of the wave-length λ_t, either on a separate sheet or to an improvised scale on the same sheet, adding a point at 561 mμ equal to that at 527.5 mμ, since test has shown these two points to have the same error. Connect these several points by straight lines. Let λ be the wave-length at which it is desired to read a value of transmission or reflectance. The correct position on the wave-length scale at which to make the reading is $\lambda+(\lambda_e-\lambda_t)$. The values of $\lambda_e-\lambda_t$ and of $\lambda+(\lambda_e-\lambda_t)$ are inserted in columns 2 and 3 of the accompanying data sheet.

"Correction should next be made for deviations of the zero curve from the 0.0 percent line, this correction being made to the 100 percent curve as well as to the curves for the various samples. To accomplish this, the values of columns 4, 5, and 7 are read from the graph sheet at the wave-lengths given in column 3, and columns 6 and 8 filled out as indicated.

"Correction is then made for deviations of the 100 percent curve from the 100.0 percent line, as indicated in column 9.

"For any one graph sheet, of course, the values of columns 2 to 6 need be tabulated but once, since the same values are applicable to all the curves run on that particular graph sheet.

"The above procedure is the correct one to use for the most accurate results. It is often unnecessary, however, to carry out each step as outlined. For example, it is possible, if desired, after plotting the $\lambda_e-\lambda_t$ curve, to note values from that curve and read values of transmission or reflectance at the corrected wave-lengths without tabulating values in columns 2 and 3. Furthermore, for nearly nonselective samples the values of $\lambda_e-\lambda_t$ may be of negligible importance in their effect on values read from the curves, and in such cases the values of columns 4, 5, and 7 are read directly at the desired nominal wave-lengths.

"It is also often practicable to ignore the zero-curve errors. This is usually true when the reflectance or transmission of the sample is high at the wave-lengths under consideration. The relative importance of this error increases, of course, as the reflectance or transmission of the sample decreases. If it is decided that the correction need not be made for the zero-curve errors, the values of columns 5, 6, and 8 need not be tabulated, the values of column 9 being then computed simply as the ratio of the values of column 7 to those of column 4.

"Cases may even arise where the deviations of the 100 percent curve from the 100.0 percent line may also be ignored. As in the other cases, one must be guided by the purpose of the measurements, the accuracy desired, and the magnitude and importance of the deviations under consideration.

"In reading values from the curves one should attempt to discount the erratic deviations from a smooth curve which are obviously due to imperfections in the operating mechanism. Such deviations are likely to be larger below 500 mμ, where the spectral sensitivity of the photoelectric cell is small.

NATIONAL BUREAU OF STANDARDS
Colorimetry Section

Serial No. CS 159
NBS Test No. 4312 - 177
Sample: 0.6 Density
Curves: 5 and 6

Data Sheet to Accompany Graph Sheet for Recording Spectrophotometer

1 True Wave Length (mμ)	2 Wave-Length Error, $\lambda_e-\lambda_t$ (Note sign)	3 Wave-Length Scale Reading, 1+2	4 100% Curve **	5 Zero Curve (Note sign)	6 True 100% Values 4-5	7 % Apparent Reflectance* Curve	8 7-5	9 Apparent Reflectance* 6/6	10
*380								O_x	
* 90									
400	-0.7	399.3	99.5	+0	99.5	50.7	50.7	.510	
10	-0.7	409.3	99.1	+0	99.1	41.8	41.8	.422	
20	-0.8	419.2	98.8	+0	98.8	29.5	29.5	.299	
30	-0.9	429.1	98.4	+0	98.4	20.4	20.4	.207	
40	-0.9	439.1	98.1	+0	98.1	14.15	14.15	.1442	
450	-0.7	449.3	97.8	+0	97.8	15.85	15.85	.162	
60	-0.5	459.5	97.4	+0	97.4	17.0	17.0	.174	
70	-0.3	469.7	97.3	+0	97.3	18.35	18.35	.189	
80	-0.1	479.9	97.2	+0	97.2	21.5	21.5	.221	
90	-0.1	489.9	97.1	+0	97.1	23.9	23.9	.246	
500	-0.6	499.4	97.0	+0	97.0	23.75	23.75	.245	
10	-0.8	509.2	96.85	+0	96.85	23.9	23.9	.247	
20	-1.3	518.7	96.75	+0	96.75	23.1	23.1	.239	
30	-1.8	528.2	96.75	+0	96.75	22.8	22.8	.236	
40	-1.8	538.2	96.65	+0	96.65	23.2	23.2	.240	
550	-1.8	548.2	96.55	-.05	96.6	24.8	24.85	.257	
60	-1.8	558.2	96.5	-.06	96.56	26.5	26.56	.275	
70	-1.3	568.7	96.4	-.05	96.45	26.5	26.65	.275	
80	-0.8	579.2	96.35	-.06	96.4	24.8	24.85	.258	
90	-0.3	589.7	96.3	-.06	96.36	22.5	22.55	.234	
600	+0.1	600.1	96.25	-.1	96.35	22.65	22.65	.234	
10	+0.6	610.6	96.25	-.1	96.36	22.55	22.65	.235	
20	+0.9	620.9	96.2	-.1	96.3	22.4	22.5	.234	
30	+0.9	630.9	96.2	-.1	96.3	22.1	22.2	.231	
40	+0.9	640.9	96.2	-.1	96.3	22.35	22.46	.233	
650	+0.9	650.9	96.1	-.15	96.25	24.3	24.45	.254	
60	+0.9	660.9	96.1	-.15	96.25	28.8	28.95	.301	
70	+0.9	670.9	96.0	-.15	96.15	36.4	36.55	.380	
80	+0.9	680.9	96.0	-.15	96.15	47.4	47.55	.495	
90	+1.0	691.0	95.95	-.15	96.1	58.1	58.25	.606	
700	+1.2	701.2	95.85	-.2	96.06	65.5	65.7	.684	
10	+1.4	711.4	95.8	-.2	96.0	67.6	67.7	.726	
20	+1.6	721.6	95.8	-.2	96.0	71.1	71.3	.743	
30	+1.7	731.7	95.8	-.2	96.0	71.8	71.8	.748	
40	+1.9	741.9	95.7	-.2	95.9	71.0	72.0	.751	
750	+2.1	752.1	95.7	-.2	95.9	71.2	71.4	.745	
* 60									
* 70									

(*) Values estimated for columns 4, 5, and 7.
(**) MgO vs MgO
(*) Relative to _____. These columns also for values of transmission
Data read by M.F.H. Date 10-4-37 Computations by M.F.H. Date 10-5-37
Data checked by K.S.G. Date 10-6-37 Comp. checked by K.S.G. Date 10-8-37

FIG. 7. Example of reduction of data on the Bureau instrument. See Section VII.

"Such erratic instrumental deviations should also be discounted in determining the wave-length errors by means of the didymium curve. One should attempt to estimate what the wave-length of minimum (or maximum) transmission would be if the curve were free of these deviations. For this purpose a transparent ruled celluloid is very helpful. A fine straight line should be cut in the celluloid and filled with india ink. This line may be placed at the center of the absorption band with considerable precision and the wave-length thereby estimated to 0.2 mμ (0.1 division). In thus centering the line one should be careful to avoid errors due to lack of symmetry of the band."

In Fig. 7 is shown the data sheet to which reference has been made in the above quotation, filled in with data applying to curves 5 and 8 of Sheet No. G.E.-159, shown in Fig. 8.

Difficulties in reading curves obtained with recording pens giving the heavier line were noted by Chairman F. L. Dimmick, particularly at intersections with the zero coordinate line. In reply attention was called to the finer line obtained with the pen used on the Bureau instrument (see introduction), barely 0.1 percent in thickness, and it was pointed out that a pair of dividers is very useful in reading values from the 100 percent and the zero curves. The points of the dividers are set one or two divisions apart; one point is placed at the center of the recorded line and the fraction of the division is read from the other point in the network.

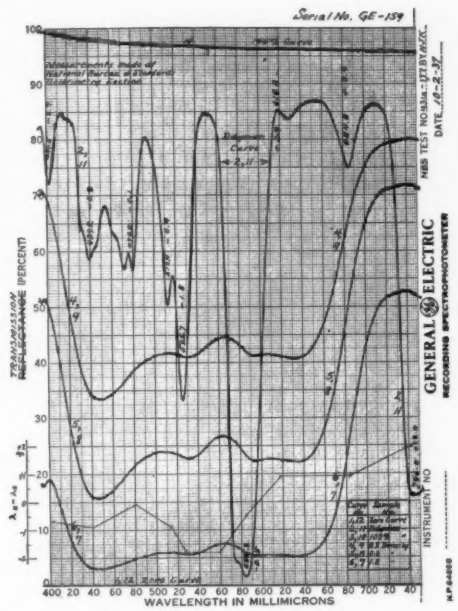

FIG. 8. Transmission curves of glasses used in a test of the Bureau instrument. See Section VIII–1.

VIII. Accuracy and Reliability

The instrument having been shown to be satisfactorily reproducible, and methods of calibration and certain precautions having been noted, it remains to consider what degree of reliability can be obtained by its use. It is to be understood, however, that any instrument may be in adjustment at one time and out of adjustment at some other time, and that what may be demonstrated for one instrument may or may not be true for another instrument. Furthermore, the accuracy obtainable often depends importantly on the sample being measured. And, in general, it is impossible to make any statement of accuracy applicable to any one instrument or type of instrument independent of the specimen being measured and the person making the measurements. The personal element is not eliminated on automatic spectrophotometers.

Nevertheless, it is possible to point out certain features of design leading to accuracy or inaccuracy and to describe certain tests and comparisons of data which will give a good idea of the reliability of the instrument. The second dispersion of the G.E. instrument apparently eliminates important errors due to stray energy. The dispersion of the energy and selection of the spectral band before incidence on the sample prevents undue heating of the sample and prevents fading of all but highly photosensitive samples during the measurement. On the other hand if the sample is excited to fluorescence by energy in the visible spectrum, the recorded curve may be importantly in error. In the following paragraphs are noted various tests of performance which have been made on the Bureau instrument.

1. The photometric scale

An important test of the accuracy of the photometric scale of this instrument was afforded

TABLE II

FILTER DESIGNATED AS	LUMINOUS TRANSMISSION, T_{2355}		
	From Curves of Fig. 8, I. C. I. Standard Luminosity	Direct observation Martens photometer	
		GWH	KSG
0.3 Density	0.4417	0.440	0.438
0.6 Density	.2515	.252	.249
1.2 Density	.0666	.0672	.0664

by the curves of Fig. 8. These curves were obtained from some "neutral" glass filters. Throughout the brighter part of the spectrum the curves are relatively nonselective, and if the luminous transmission of the filters be computed, the effect of residual wave-length errors will be very small, because the transmissions on the steep parts of the curves in the red and violet are weighted lightly by the luminosity (visibility) function. Likewise, directly measured luminous transmissions should be of reasonably good accuracy regardless of the observer's luminosity curve. Accordingly, values of luminous transmission for 2355°K were computed from the spectral transmissions derived from the curves of Fig. 8, applying zero, 100 percent, and wave-length corrections, and were compared with values of T_{2355} obtained with the Martens photometer by two experienced observers. The values in Table II were obtained. Note that in two of the three cases the computed value lies between the observed values, and that the maximum difference between computed and average observed is but 0.6 percent of the value.

A second test of the scale, independent of possible wave-length errors, has been afforded by measurements on a piece of borosilicate crown glass. Values derived from measurements on the G.E. spectrophotometer, making the 100 percent corrections, differed from values computed from the refractive index (the absorption being negligible) by not more than 0.1 percent throughout the whole visible spectrum.

And in general we may say that, when everything has been in proper working condition, we have never demonstrated the existence of any error in the photometric scale of the Bureau instrument.

TABLE III. *Comparative values of spectral transmission of glass designated as Corning H. T. Yellow α^7.*

λ (mμ)	ADOPTED VALUES 7/24/33	VISUAL 1/30/36	G.E. 56 1/8/37	G.E. 56 ×5 1/8/37	G.E. 97 3/26/37	G.E. 181 12/14/37
404.7	0.0325		0.029	0.036	0.036	0.034
420	.031		.026	.033	.033	.033
435.8	.0399	0.0400	.035	.041	.041	.042
471.3	.114	.1135	.110	.116	.118	.118
491.6	.203		.203		.211	.211
501.6	.256		.256		.263	.264
520	.367	.366	.366		.374	.372
530	.431		.430		.437	.436
546.1	.529		.526		.529	.533
560	.597		.594		.600	.600
578	.671	.672	.668		.670	.672
587.6	.697		.698		.700	.702
600	.728		.728		.730	.732
620	.757	.758	.758		.760	.760
640	.770		.772		.774	.774
660	.775	.780	.778		.779	.781
690	.775		.778		.780	.780
720	.767		.771		.774	.773
750	.751		.756		.758	.759

2. Comparisons of spectral transmission

A more rigid test of performance than those given in the previous section is given, however, by repeated measurements on a certain standard glass designated as Corning H.T. Yellow α^7. The data are given in Table III.

Values of spectral transmission had been adopted for this glass in 1933 as a result of extensive measurements on it and similar glasses by both visual and photoelectric methods, this in connection with the preparation of standard glasses for testing spectrophotometers.[12] Visual measurements at certain wave-lengths were repeated on this glass in January 1936, as noted in Table III.

This glass has been run on the G.E. spectrophotometer at three different times since the instrument was installed in June 1936. The values obtained are also shown in Table III. In considering these values it is not to be thought, of course, that the values adopted in 1933 are without error. There is uncertainty in the last figure given in all cases. And it may also be stated that the check on the adopted values obtained in 1936 is better than has sometimes been obtained in similar tests on other glasses.

It may be seen that the differences between the adopted values and the G.E. values are in

[12] K. S. Gibson, G. W. Walker, M. E. Brown, J. Opt. Soc. Am. **24**, 58 (1934).

all cases less than 0.01. This is partly the basis for the following statements which appear in the memorandum accompanying Bureau test reports based on data obtained with the G.E. instrument:

"If the data are reduced as explained above, the results will usually be in error by less than 1.0 unit on the scale from 0.0 to 100.0. With two types of curve, however, the error may readily exceed that just estimated: (1) If the curves are steep, a slight residual wave-length error will importantly affect the values obtained. (2) If the curvature is sharp, as around the absorption maxima of the didymium glass, the 4-mμ slits may include too much of the spectrum for the most accurate analysis. The true value of the transmission at the wave-length of maximum absorption will in such cases be less than that read from the graph."

Nevertheless, the variations among the G.E. data and the differences between these data are in some cases larger than desirable. This is particularly true in the neighborhood of 500 mμ, which happens to be near the region of greatest slope for this curve. This, of course, suggests that wave-length errors are still present, though other sources of error are possible. On the visual instrument stray light is particularly bothersome in this region because there are no satisfactory filters for its elimination, those available having very low transmission. The values at 491.6 mμ obtained originally with the Hg arc and 0.5 mm slits are now considered less reliable than formerly, due to the fact that a considerable amount of continuous spectrum is included by use of such slit-widths along with the homogeneous light at 491.6 mμ.

Since one set of G.E. data (No. 56) agrees closely with the adopted values in this region, this would seem to indicate that the other two sets of G.E. data were definitely in error. However, the authors afterwards had reason to suspect, though they were not certain, that the cam had not been correctly adjusted to its normal position on G.E. 56; and it may be noted that the values obtained with the $\times 5$ cam at the same time do agree better with the later sets of G.E. data. Usually the data obtained with the normal cam and with the $\times 5$ cam agree much better than illustrated by the data of G.E. 56. The data are instructive, however, as indicating the order of magnitude of differences obtained, both between methods and between different sets of data obtained on the G.E. instrument at different times. It is the most extensive set of data of this type available at the Bureau and was chosen for illustration for this reason.

The tendency of the data obtained on the G.E. instrument to be slightly higher than those obtained on the König-Martens spectrophotometer, illustrated to some extent by the data of Table III, has often been noticed on other glasses. This may be due to the fact that strictly the two instruments are not measuring the same quantity. On the K-M instrument the aperture of the used part of the transmitted beam is very small, only a few degrees. On the G.E. instrument, while the beam aperture is likewise small, the sphere opening covers about half the subtended hemisphere. The G.E. instrument will therefore include in the measurements much of the transmitted energy that is scattered by surface imperfections, striae, inclusions, etc., whereas this scattered energy is nearly all excluded in the K-M apparatus. Even on fairly good specimens the difference may amount to nearly 1 percent of the value. On obviously poor samples the difference would of course be much greater.

If one is interested in measuring all the transmitted energy, diffused or not, the instrument should be altered so that the sample may be placed against the sphere opening. This has been done on the G.E. instrument in the Eastman Kodak Laboratories, and the present design of the commercial instrument facilitates placing the sample next to the sphere opening.[13]

3. Spectral reflection data

Reference was made in the introduction to the quantity that is measured on the G.E. spectrophotometer. This should be clearly remembered in any comparisons of data obtained on this instrument with data obtained on any other type of spectrophotometer. Tests at the Bureau have shown that with glossy samples, as expected, values obtained on the G.E. instru-

[13] See paper by Mr. Michaelson, preceding this paper.

TABLE IV. *Effect of a uniform 1-mμ error throughout the wave-length scale on x, y, z, and T_A for representative signal glasses with I. C. I. illuminant A.*

Signal Glass						
Color Designation	Number	Δx	Δy	Δz	Max. Δx or Δy	$\frac{\Delta T_A}{T_A}$ (%)
Red	86	.0007	.0007	.0000	.0007	5.6
Yellow	—	.0018	.0017	.0001	.0018	1.0
Yellow	142	.0013	.0010	.0003	.0013	1.1
Green	87	.0022	.0045	.0067	.0045	2.1
Blue	47B	.0004	.0022	.0018	.0022	3.0
Purple	47P	.0019	.0007	.0012	.0019	2.8
Lunar White	73	.0008	.0007	.0001	.0008	0.7
Ave.					.0019	

ment are intermediate between those obtained on the K-M spectrophotometer on which completely diffused illumination and normal viewing are used and those obtained on the McNicholas-Hunter goniospectrophotometer when normal illumination and 45° viewing are used. These differences are due, of course, to the degree of inclusion of the specularly reflected light in the measurements. A much improved situation would result, so far as the G.E. instrument is concerned, if the design were such that this specular component of the reflected light could be either entirely included in, or entirely excluded from, the measurements, at will. It is planned eventually to do this on the Bureau instrument.

4. Effect of spectrophotometric errors on computed colorimetric values

It is difficult to make any general statements as to the effect of spectrophotometric error on computed colorimetric values; it depends too importantly on the sample itself. For example, failure to correct for the 100 percent curve may importantly affect the colorimetric values for a white sample, but will be of little or no consequence for a very dark sample; failure to correct for the zero curve may importantly affect any sample whose curve lies close to zero at some wave-lengths, but will probably be negligible for white samples; failure to correct for wave-length errors will be most important for highly selective samples, but will be of no consequence with nonselective samples.

However, various data have been accumulated which have important bearing on the magnitudes of errors or differences in computed colorimetric data resulting from these and other possible sources of error in the spectrophotometric data.

(a) *Effect of 1-mμ wave-length error.*—The erratic deviations from the correct wave-length illustrated by variations of $\lambda_c - \lambda_t$ from the average value, as illustrated in Fig. 6, depend on the cams of each particular instrument. If the sheet is correctly inserted in the best average position the effect of such wave-length errors on computed colorimetric values will, on the Bureau instrument, usually be less than that caused by a 1-mμ error of the whole scale caused by either inexact insertion of the paper or inexact adjustment of the height of the recording pen. The effect of a 1-mμ error in the values of the trichromatic coefficients, x, y, z, and the luminous transmission for illuminant A, T_A, all on the 1931 I.C.I. basis, have been computed[14] for six signal glasses representative of the most highly selective samples that will ordinarily be measured. The values are given in Table IV.

(b) *Effect of small errors in 100 percent and zero curves.*—Occasion was recently taken to repeat the computations of x, y, z, and T_C for the two blue glasses shown in Fig. 2, G.E. No. 193. On this sheet the average 100 percent curve differs from the 100 percent coordinate line by not more than ±0.1 percent, this agreement being so good that the 100 percent values had been assumed as 100.0 at all wave-lengths in the first computations. (Zero corrections were, however, made to the spectral transmission readings and the assumed 100.0 readings in the computations.) Recomputation with the values of spectral transmission corrected for the slight deviations of the average 100 percent curve gave the following differences in the respective values from those originally obtained:

Glass	Δx	Δy	Δz	$\Delta T_C/T_C$
Daylight	0.0000_8	0.0000_6	0.0001_2	$0.0_5\%$
Cobalt	$.0000_8$	$.0001_7$	$.0002_6$	$.0_5\%$

While these values are negligible in themselves, they indicate that deviations of 1.0 percent in the 100 percent curve would often be too important to ignore.

In another case, that of a Munsell *RYR* 5/6 sample (NBS Test 433z–178) computations were

[14] These results were presented at the Color Conference held at M. I. T. in July, 1936.

made both with all corrections applied and also with the 100 percent and zero corrections neglected. The following differences were obtained, A referring to the apparent reflectance of the sample:

$$\Delta x = 0.0009$$
$$\Delta y = .0005$$
$$\Delta z = .0013$$
$$\frac{\Delta A}{A}(\%) = 0.2$$

On this particular sheet the 100 percent curve varied from 99.8_5 to 100.1 and the zero curve from $+0.2$ to -0.1_5. Most of the difference shown results from the zero correction rather than the 100 percent correction.

(c) *Effect of errors in reading curves.*—Two observers reading values from transmission or reflection curves at agreed-upon corrected wave-lengths will in the great majority of cases differ by not more than 0.1 on the scale from 0.0 to 100.0. Differences of 0.2 are often obtained, however, and occasionally still larger ones, particularly on steep curves. These refer to differences of judgment, not blunders. Here, as in all other such cases, the effect of the error on computed values depends on the sample. In the case of a certain yellow paint panel with steep curve (NBS Test 4311*ik*–195), two observers read and computed values independently, using the same wave-length corrections. The following differences were obtained:

$$\Delta x = 0.0003_5$$
$$\Delta y = .0003_8$$
$$\Delta z = .0000_3$$
$$\frac{\Delta A}{A}(\%) = 0.2$$

TABLE V. *Colorimetric values computed for three orange panels of varying gloss. Illuminant and heterogeneous stimulus: I. C. I. illuminant C.*

Sample	Specular Component	Luminous Apparent Reflectance A	Trichromatic Coefficients x	y	z	Dominant Wave-Length λ ($m\mu$)	Colorimetric Purity p_c
1	In	0.373	0.5025	0.4131	0.0845	587.2	0.828
	Out	.340	.5276	.4257	.0467	587.2	.908
	Diff.	.033	.0251	.0126	.0378	0.0	.080
2	In	.337	.5059	.4051	.0890	588.6	.815
	Out	.320	.5194	.4112	.0694	588.6	.858
	Diff.	.017	.0135	.0061	.0196	0.0	.043
3	In	.326	.5198	.3998	.0804	590.3	.831
	Out	.286	.5582	.4151	.0267	590.3	.947
	Diff.	.040	.0384	.0153	.0537	0.0	.116

These differences were traced mostly to differences in reading at four corrected wave-lengths on the steep part of the curve; these differences of reading varied from 0.2 to 0.5 on the scale from 0.0 to 100.0.

(d) *Effect of specular component of reflection on computed values.*—It was stated above that the G.E. instrument includes part but not all of the specularly reflected light. The effect of this component on computed colorimetric values may be very large. On a certain test (80232, Supplement) of three orange panels of varying gloss, the values of Table V were derived. The following points may be noted:

1. The degrees of gloss are indicated by the differences in the values of A with specular component in and out, the gloss for No. 2 being the lowest, that for No. 3 the greatest.

2. The differences in colorimetric purity, p_c, with specular component in and out, are large and correlate notably with the gloss.

3. The dominant wave-length, λ, is unaffected by the specular component.

4. The effect on the x and y values is very large. With a sample of high gloss, No. 3, the difference is seen to be nearly 0.04.

5. Values obtained on the G.E. instrument would be intermediate between those given for the respective "in" and "out" values. The "correct" values depend, of course, on the purpose of the measurements, and it must be decided in each case, first whether any correction to the measured values is necessary or desirable, and second whether the corrections should be made so as to include or exclude the specular component of the reflected light.

(e) *Effect of fluorescence.*—If the sample being measured is excited to fluorescence by energy in the range of spectrum covered by the instrument, important errors may result because the fluorescent energy reaches the detector without further prismatic dispersion. This subject was considered by the authors at the February meeting of the Optical Society of America and the reader is referred to the proceedings[15] of that meeting for further details. In the instance cited the error in the x and y coordinates was of the order of 0.03.

[15] J. Opt. Soc. Am. **28**, 180 (1938).

Application of Spectrophotometric Data in the Printing Ink Industry*

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(Received July 5, 1938)

PRINTING ink consists essentially of fine particles of a pigment dispersed in a vehicle. The ink is applied by suitable printing procedures to a variety of surfaces in films that vary from 2 to 10 microns in thickness. These ink films present very complex optical problems for which spectrophotometry provides the most complete solution.

Few commercial applications of spectrophotometry in this field were made until recently, when an automatic photoelectric recording spectrophotometer, having sufficient accuracy, precision, speed, and ease of operation, was developed. This paper is a progress report on the principal applications that have been made with data obtained with the General Electric model of the Hardy spectrophotometer, which has been in operation in the Research Laboratories of the Interchemical Corporation since June, 1935. Prior to its installation, many routine measurements were made at the Color Measurement Laboratory of the Massachusetts Institute of Technology as soon as their instrument was placed in operation in January 1933.

When measuring the color of printing ink, the sample is likely to be in the form of a dried ink film on some reflecting surface such as white paper. The spectral reflection properties are usually determined relative to magnesium oxide, which serves as the white standard. Color standards maintained in this manner are not susceptible to the possibilities of "drift," which is very common in attempts to preserve material standards.

Since all printing inks are more or less transparent when the film thickness is of the order used in most printing methods, the color of the print depends upon the color of the surface on which the ink is applied as well as upon the color of the ink film. While the color of the support material can be measured, and the color of the ink alone determined, this is not the most desirable method, because other physical characteristics of the support have a definite effect on the color of the ink film. If there is any penetration of the vehicle into the support, this will result in a change in the pigment-vehicle ratio of the ink film and the color of the ink film will be somewhat different. Other factors, like gloss, which affect the appearance, will also undergo change. However, the spectrophotometric curve gives more useful information about the color than is possible by other color-measurement methods. With experience, it is possible to recognize the kind or chemical class of coloring components and, to a certain extent, the amount of each present.

Spectrophotometric data may be compiled which will serve as file information, but it is desirable that this information be of the ink alone. A method has been developed which will allow for the measurement of the color of the ink largely independent of the support. As the index of refraction of the printing ink vehicle is very similar to that of glass, it is possible to use glass substandards for this measurement work. If the ink film is applied over a white substandard and compared against a duplicate white substandard, the resultant measurements depend on the transmittance of the ink and the reflectance relative to the white substandard. If the ink film is applied over a black substandard, and measured *versus* the previous white substandard, the resultant measurements give only the reflectance relative to the white substandard. In this way, a separation of the transparent and opaque components of the ink film may be made. See Figs. 1 and 2. This separation is advisable because of the peculiar nature of most printing ink films for reasons which will be apparent later. Additional information can be obtained by making the above comparisons against magnesium oxide. Since the color of ink varies with film thickness, measurements of a gamut of film thicknesses for each case must be made in order that adequate information will be provided.

* Invited paper presented at the seventh annual meeting of the Inter-Society Color Council held at the Electrical Testing Laboratories, New York, February 24, 1938.

Glass plates provide the best surfaces for the repeated application of ink and for ease of cleaning, and allow no penetration of the vehicle. These substandards are very permanent and should be nonselective in their reflection properties. Certain grades of white opal glass and black glass are sufficiently opaque in thicknesses of about 1 inch for the former and $\frac{1}{4}$ inch for the latter and have proved satisfactory. Measurements are usually made with wet ink films in order to avoid the time delay that drying would entail.

Measurements of each principal pigment dispersed in a vehicle at a particular concentration have already been made by this method for appropriate film-thickness gamuts. This work is being continued and common mixtures of chromatic pigments with chromatic and with white pigments are being included. These data make possible the identification of the kind and also the amount of each pigment component in unknown inks to a remarkable extent. The attachment of a film-thickness scale would be of additional value, but the inclusion of this information depends upon the development of a convenient and sufficiently accurate method for determining film thickness.

The usefulness of the above information is evident when the problem of color matching is considered. With information regarding the coloring components of an unknown sample, it is relatively simple to achieve a spectrophotometric match. Spectrophotometric matches are to be desired because such matches are not affected by variations in the quality of the illumination.

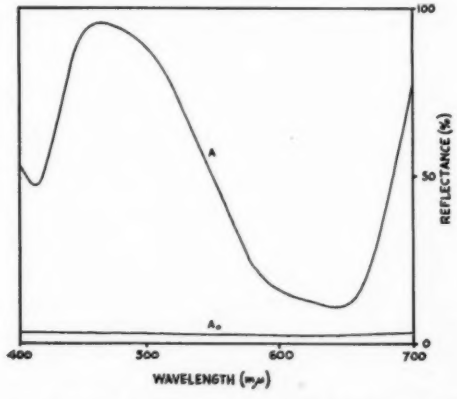

FIG. 1. Curve A shows the spectral reflectance of a film of blue ink applied to the surface of a white glass substandard. Curve A_0 shows the spectral reflectance of the same ink at the same film thickness when applied to the surface of a black glass substandard. Because of the absence of scattering of light in the ink film, this ink would be classed as "transparent."

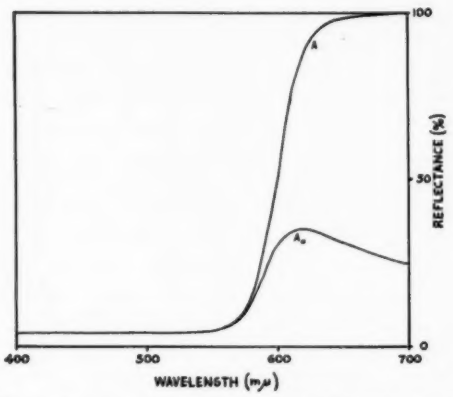

FIG. 2. Curve A shows the spectral reflectance of a film of red ink applied to the surface of a white glass substandard. Curve A_0 shows the spectral reflectance of the same red ink at the same film thickness when applied to the surface of a black glass substandard. The reflectance values in both cases are relative to a white substandard which is a duplicate of the white glass used in the first case. Because of the scattering of light within the ink film, this ink would be classed as "semi-transparent." Some inks exhibit so much scattering that they are commonly called "opaque." In such cases, curve A_0 approaches curve A.

With the conversion of the above spectrophotometric data to colorimetric terms, in accordance with the method described in a report of the 1931 International Commission on Illumination, still more purposes can be served. The color gamut of each particular ink can be represented on graphs with dominant wave-length and excitation purity as coordinates and on graphs with relative brightness and excitation purity as coordinates.

The complete work on the relation of color and composition of ink will be of extreme value for visual matching as well as for matching when a spectrophotometer is available. With these spectrophotometric and colorimetric data on base inks at hand, experienced color matchers can apply film thickness and mixture data to visual matching with significant advantages. An understanding of the above greatly reduces the possibilities of poor color matching of the kind where samples are a match under one quality of illumination, and different under others.

Spectrophotometry makes possible a more thorough study of the opacity of an ink than has been practiced heretofore. As the opacity of an ink film varies with the pigment-vehicle ratio, particle size, and refractive index, data may be compiled for a particular pigment for a variable film-thickness gamut and a variable pigment-vehicle ratio. Films are applied over a black substandard and their reflectances measured relative to a magnesium oxide standard. The black substandard should have properties as outlined for the previous case, and measurements can be made either of wet or of dry films. While the correlation of these three variables gives very useful information, certain problems may be solved by measurements of the reflectance of completely opaque films for different pigment-vehicle ratios.

It is sometimes desirable to make measurements of the pigment alone, and this is done by compressing the dry pigment in an appropriate device. Pellets suitable for measurement can readily be duplicated by reasonable control of the pressure. About two hundred pounds per square inch has proven satisfactory to produce pellets of sufficient rigidity without introducing additional first surface complications due to excessive pressure. The color of certain vehicles has been determined by transmission measurements and this information is considered with pigment measurements for special purposes.

Spectrophotometric data of inks made from newly developed or previously unused pigments have been of extreme value in indicating possible uses for these materials that would not be evident from visual observation. It has also been helpful in the improvement of coloring materials by providing a way to distinguish small apparently undetectable differences between pigments made by varied processes. By planning the synthesis to take advantage of the plus increments, significant improvements can be made.

Certain pigments are sensitive to the action of radiant energy and undergo changes in reflectance with time. See Fig. 3. The changes are the result of very complex photochemical actions which may or may not be reversible. Spectrophotometry provides the only exact measurement of the change, which depends in kind and rate upon a number of conditions. In the case of the permanent change, commonly referred to as "fading," the time is usually of the order of hours and days with considerable amounts of radiant energy, while in the case of the reversible change, the time is usually of the order of seconds and minutes with small amounts of energy and the recovery at much slower rates. Where the change is over a wide range, it is desirable to determine the kind of change with periods of time. The conversion of these spectrophotometric data on the I. C. I. colorimetric basis provides an excellent picture of the change.

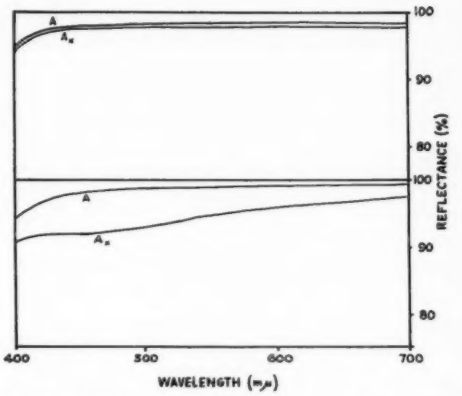

FIG. 3. These curves indicate the change in reflectance upon exposure to radiant energy of two different samples of dry titanium dioxide. Curve A in each case is for the dark-adapted sample, while curve A_x is for the same sample after exposure to radiant energy. The lower set of curves exemplify the maximum change that has been noted while the upper set is typical of the commercial products. Many other white pigments show a similar effect.

The spectrophotometric measurement of the reversible change referred to as "light sensitivity" requires special techniques of sample preparation. The method that has been developed depends on the complete dark adaptation of the sample for a period of twelve hours or more. The sample is then measured without exposure to radiant energy other than that used in the measurement. Because of the design of the Hardy spectrophotometer, the amount of this incident energy is extremely small and its effect during the time period of measurement is also small. This curve is compared with another curve for the same sample after exposure to daylight energy for a period sufficiently long to show practically all of the photochemical action.

If the rate of change is to be determined, the wave-length at which the greatest difference occurs between these curves is selected for further measurements. This difference may be a gain or loss, and often varies with wave-length. Another dark-adapted sample is then measured and exposed for various intervals of time. Reflectance readings for the selected wave-length are taken from the indicator on the spectrophotometer. A graph of reflectance-change *versus* time may then be prepared.

Similar techniques may be used to determine the bleaching action of radiant energy on the vehicles as well as the darkening or yellowing of vehicles with time without exposure to radiant energy. Other color changes, such as are brought about by the action of heat or by other actions, may also be recorded.

As all reflectance measurements with the spectrophotometer are relative to the reflectance of the standard, it is very important that the standard remain constant. It has been noticed that the reflectance of the magnesium oxide standard depends upon the purity of the magnesium, conditions of preparation, and age. The stability of magnesium oxide depends upon the purity of the magnesium and certain other factors now under observation. After one day, its reflectance decreases, beginning at about 550 mμ and becoming more noticeable with decrease in wave-length. At 430 mμ the order of change is 0.2 percent or 0.3 percent. After one week, the loss in reflectance may range from 0.5 percent to 2 percent. No significant change of reflectance from 550 to 700 mμ has been detected. Satisfactory standards can be prepared in fifteen minutes and the reflectance of successive preparations usually varies less than 0.2 percent.

In certain printing inks, an unusually selective reflection may be noticed, which varies considerably with viewing conditions. This is to be distinguished from the kind of selective reflection that varies but little with angle of view. The first is designated as "bronze" while the second is due to opacity in the ordinary sense. These two kinds of reflection plus the nonselective first surface reflection have been referred to earlier as the opaque component because they all refer to a reversal in direction of flow of radiant energy.

In the case of the completely transparent inks, where there is no opacity, the bronze plus first surface reflection is the property measured when the sample is applied over a black substandard under conditions previously described. It has been noticed that bronze varies with pigment-vehicle concentration and with the first surface of the film. Diffusely reflecting first surfaces seem to enhance bronze, while smooth glossy surfaces seem to decrease bronze. This reduction in bronze is probably due to the greater vehicle percentage in glossy inks. As the concentration of pigment is increased, the bronze is also increased. Goniometric methods will be of considerable value in the further study of the bronze phenomena.

There is the possibility of encountering difficulty from fluorescence in the measurement of printing inks with the Hardy spectrophotometer, but no evidence of this effect has been found in the materials that have been studied to date.

Probably the most significant applications of spectrophotometry have been made in the field of color reproduction. The colored illustrations in magazines are produced by printing methods usually referred to as "process" printing. Printing plates made by halftone and other processes are used to make possible the production of intermediate colors by the super-imposition of various amounts of the several printing inks. By the use of three transparent inks of the proper color, a gamut including most of the colors of natural objects may be achieved. The spectrophotometric requirements for the ideal process inks have been set up and all likely coloring materials have been evaluated on the basis of their approach to these ideal colors. It was noticed that certain materials which have never been used for process inks would give results better than previously obtained.

The success of a process print depends upon the proper relation between the colors of the inks and the characteristics of the filters used in making the "color separations." This fundamental relationship, which is basic to the theory of color reproduction, has been studied and has resulted in the disclosure of serious errors in the theories on which present practice is based. New techniques have been devised which will result in more exact color reproduction.

Designation of Filters for Theatrical Lighting*†

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(Received July 5, 1938)

The basis of this proposal is that the complete definition of the chromatic properties of filters used in illumination is transmission as a function of wave-length; an approximate definition suitable for commercial specification should, therefore, take the form of an abbreviated notation for the curve of spectral transmission. It is proposed to specify filters for theatrical lighting by a seven-digit number, the first digit of which refers to spectral transmission at the short wave extreme of the spectrum, the second, that at some longer wave portion, and so on throughout to the long wave extreme. The present paper discusses choices of wave-lengths to which the digits should refer and also what range of transmission should be indicated by digit, 0, what by digit, 1, what by digit, 2, and so on for maximum usefulness of the specification. Recommended choices are presented based upon a spectrophotometric examination by William F. Little and Allan E. Parker of the Electrical Testing Laboratories made upon two groups of theatrical gelatines, one group of 11 pink filters and one group of 11 blue filters.

I. HISTORICAL

THE problem of devising a simple specification of filters used for theatrical lighting was informally brought before the Inter-Society Color Council in 1932 by A. L. Powell of the Illuminating Engineering Society. He asked that the Council recommend "terminology of glasses, gelatine, and other media for the production of colored light flux." This problem was discussed by the Committee on Color Problems at its first meeting, April 26, 1932, Washington, D. C. There was considerable difference of opinion among the committee members and according to the report of the chairman, Margaret Hayden Rorke, it was "decided that the problem had so many ramifications and was such a vital one that it should be officially submitted by a Society such as the Illuminating Engineering Society rather than by an individual, and that a letter should be written to Mr. Powell, expressing the Committee's appreciation for bringing the problem to its attention, and urging that he interest the Illuminating Engineering Society or any other scientific organization, of which he is a member, to sponsor this problem officially and represent it to the Council for future action." This was never done, however; and the problem lay dormant until the 1937 Annual Meeting of the Council.

At that meeting work on the problem was reopened by the author who, in his capacity as present chairman of the Committee on Color Problems, proposed a tentative specification for such filters. This proposal was discussed by the Council,[1] and it was presented before the New York Section of the Illuminating Engineering Society by the author in an invited address sponsored by the Council. Discussion following this presentation was generally favorable except for questions as to details of the arbitrary choices of the wave-lengths and of division points in the transmission scale. A. E. O. Munsell, delegate from the Optical Society of America, made some very specific recommendations for revision of the latter; these were accepted as improvements by the present chairman, and appear in Appendix E to the minutes of the 1937 Annual Meeting.

This plan of specification was then brought before the December, 1937 meeting of the Executive Committee of the Inter-Society Color Council who instructed William F. Little, delegate from the Illuminating Engineering Society, to get in touch with filter manufacturers for the purpose of learning what might be done to put the specification into effect. As a preliminary step Mr. Little obtained samples of theatrical gelatines from two manufacturers, and selected from them two groups of similar filters with which to test the proposed specification to see if it would distinguish between all filters

* Invited paper presented at the seventh annual meeting of the Inter-Society Color Council held at the Electrical Testing Laboratories, New York, February 24, 1938.

† Publication approved by the Director of the National Bureau of Standards of the U. S. Department of Commerce.

[1] The proposal is stated in Appendix E to the minutes of the 1937 Annual Meeting; the discussion is summarized in the minutes.

commercially different. One group consisted of 11 pink filters, and the other of 11 blue filters. The spectral transmissions of these 22 filters were obtained and examined by Allan E. Parker at Electrical Testing Laboratories. From his examination of these data, Mr. Parker was able to suggest improvements in the proposed specification.

It is the purpose of the present discussion to give briefly the theoretical basis of the specification, to give the details of the various arbitrary choices so far proposed together with the argument by which they may be supported, and to give details of what is believed to be a still further improved plan of specification which is here recommended for adoption.

II. Theoretical Considerations

Filters are in general use in stage illumination in combination with spot lights or flood lights for producing chromatic effects. The illuminants are chiefly incandescent lamps and carbon arcs. The chromatic effects do not consist merely in projecting spots or areas of chromatic light on a stage filled with nonselectively reflecting (white or gray) objects, but more generally to illuminate selectively reflecting objects, painted scenery and players covered by costumes and cosmetics, which in daylight or incandescent-lamp light display highly chromatic colors.

The designation of the glass or gelatine filters now used for theatrical lighting is by trade names and numbers assigned to them by each manufacturer, the central part of the name for most filters being a color name. The color name serves a very useful purpose by indicating in a general way the appearance of nonselectively reflecting objects illuminated by light projected through the filter. The trade number serves a further useful purpose by providing additional assurance that a "repeat order" from the same manufacturer will be a satisfactory substitute. However, there is little or no correspondence between the designations of different manufacturers nor does this system of designation lend itself to logical expansion or interpolation as new and improved chromatic media are developed.

It might seem that this problem could be solved by promoting an agreement among manufacturers to use the same numbers for the arbitrary designation of filters. The trade numbers now used indicate to the manufacturer the coloring materials in the filter. But since there are, particularly for gelatine filters, so many possible coloring materials, an impractically large list would be required; furthermore, many different dyes will produce what is commercially the same filter, hence, an arbitrary system of numbering would not serve to identify commercial duplicates.

A frequent suggestion is that a colorimetric designation of the illuminant-filter combination is needed; this would require three numbers and would take the form of a tristimulus specification, or the form of a specification by dominant wavelength, colorimetric purity and transmission. Thus, two illuminant-filter combinations having the same colorimetric specification would produce illuminating beams which color-match. This form of specification would be quite suited to filters to be used to illuminate nonselectively reflecting objects (whites or grays) only. But there are filters which would have the same colorimetric specifications yet would produce radically different chromatic effects when used to illuminate an array of selectively reflecting objects. For example, it is easily possible to find two filters, identically blue by carbon-arc lamp, one of which transmits freely the long wave portion of the spectrum, the other of which transmits it scarcely at all. These filters produce the same chromatic effect upon nonselectively reflecting objects (whites and grays) but one brings out red objects brilliantly, while the other makes them look dark gray.

The presence upon the stage of selectively reflecting objects, requires, therefore, a much more complicated numerical specification of the filters used in theatrical lighting. Instead of three numbers for each filter, the spectral transmission throughout the visible spectrum would have to be given. This is the final and fundamental specification; two filters having the same curves of spectral transmission cannot fail to produce the same chromatic effect. To make sure of this identity to the degree that an observer would be able to detect no difference between filters of identical specification would require the use of about 30 values instead of 3. These 30 would

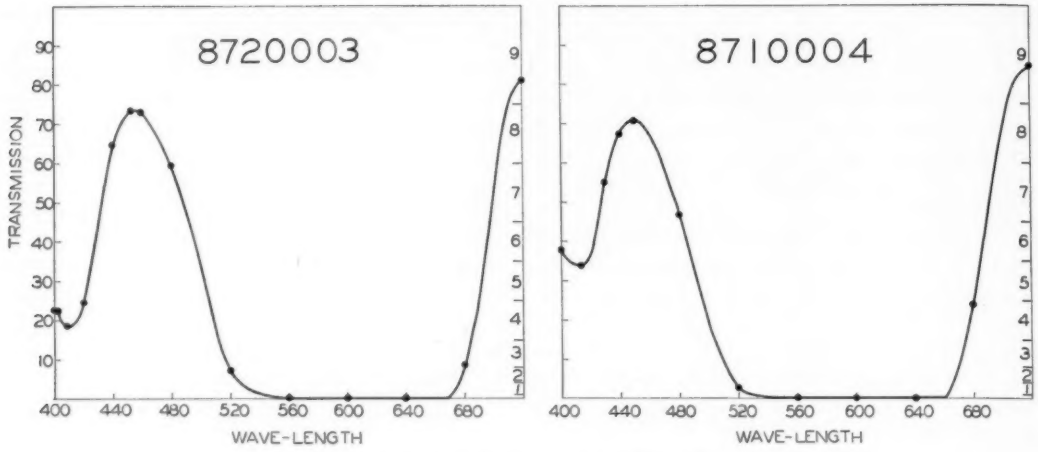

FIG. 1. Spectral transmissions of two blue filters.
They are now designated by the distributor: Medium Blue No. 33 and Medium Navy Blue No. 34; the proposed ISCC designations are 8720003 and 8710004. This pair of filters illustrates closely the smallest difference which would be certainly differentiated by the proposed ISCC system of designation.

adequately specify the curve of spectral transmission for any colorimetric use of the filter. Obviously, however, a 30-parameter designation of filters for theatrical lighting is impractical.

The specification proposed here gives an abbreviated notation for the curve of spectral transmission. Each filter is to be specified by a seven-digit number, each digit indicating approximately (on a scale of ten) the spectral transmission at some wave-length. It is hoped that the loss in accuracy necessitated by accepting a 7-parameter approximate specification instead of a 30-parameter accurate specification will not result in confusing two filters which are commercially different. As a justification for this hope it will be noted that the proposed system provides for the specification of 10,000,000 different filters. This number would seem to be large enough to embrace theatrical needs for some time to come. There remains the problem of making arbitrary choices of wave-length and transmission range so as to make the most practical use of these 10,000,000 specifications.

III. Arbitrary Choices

For the number of parameters to be used in the abbreviated notation seven was chosen because it is about the limit of the average memory span. It is usually possible to repeat without error any seven digits an instant after they have been given; to repeat eight is considerably more confusing.

Next we have to choose what 7 wave-lengths are to be used in the seven-digit specification; and we have to decide what transmission ranges are to be denoted by the digits, 0, 1, 2, and so on.

A. Selection of wave-lengths

The visible spectrum extends roughly from 380 to 770 mμ. The 7 points should be distributed somewhere throughout this range rather more toward the middle than toward the extremes because of the small chromatic contribution made by the extremes. To make the choices easy to remember, the distribution should be uniform.

For a tentative choice of wave-length interval 50 mμ was taken; that is, the first digit would apply to 400 mμ, the second to 450 mμ, and so on up to 700 mμ. The groups of filters examined by Little and Parker indicated, however, that a 50 mμ interval is too large; they showed many examples of filters in which the spectral transmission changed so rapidly with wave-length that a 50 mμ interval might permit important differences in spectral transmission to go unspecified. See Fig. 1 in which two blue filters, one of which brings out red objects somewhat more than the other, differ considerably between

670 and 700 mμ; this difference falls within a 50 mμ interval and would not be shown, for example, either at 660 or 710 mμ. A smaller wave-length interval is therefore needed—obtainable either by using more than 7 digits or by restricting the specification more to the center of the spectrum. Since a 7-digit number has already been fixed upon as the longest number for convenient use, the second possibility was investigated. It was found that neglect of the spectrum extremes brought no undesirable deficiencies in the specification of the filters so far measured. A 40 mμ interval starting with 440 mμ and ending with 680 mμ has therefore been adopted.

In the discussion at the Council meeting, the suggestion was made by K. S. Gibson, National Bureau of Standards, that a first digit, set off from the other seven by a dash, be used to indicate which of ten possible groups of seven wave-lengths is indicated. If the proposed system should be found insufficiently discriminative, this suggestion is worth further study because it increases the flexibility of the specification. A disadvantage is that it increases the complexity of the specification by giving 10 possible designations for each filter instead of a single one.

Other questions during discussion were aimed at selection of wave-lengths in accord with some more apt principle than the two actually followed. L. C. Lewis, Meade Corporation, suggested that uniform distribution throughout the visible spectrum be given up in favor of choosing the seven most important wave-lengths; Verne H. Rechmeyer, Agfa Ansco Corporation, suggested that wave-lengths might be chosen to accord with the stimuli for typical red, orange, yellow, green, blue and violet. In reply, it should be noted that an obstacle to selection of the seven most important wave-lengths is that we do not know what they are, but we do know that the stimuli for the seven Newtonian hues are not the

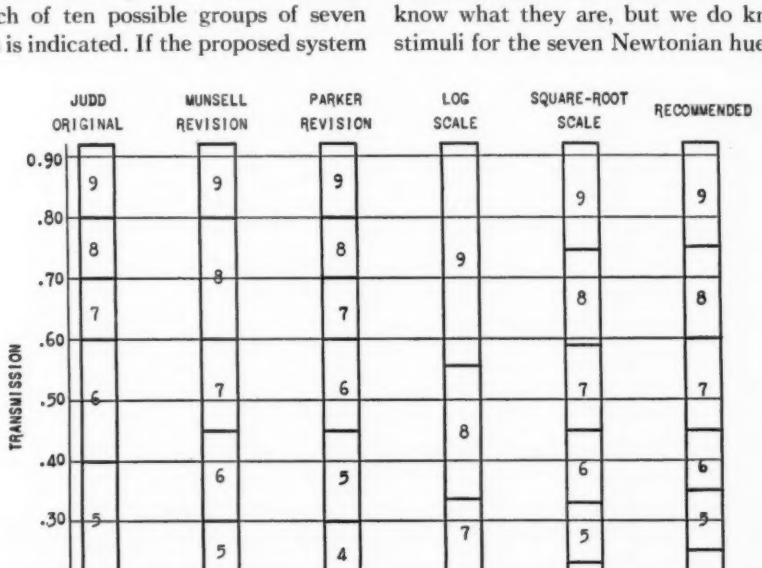

FIG. 2. Divisions of the transmission scale.
Four proposed arbitrary divisions including the recommended division, and two systematic divisions are shown. The recommended division is also indicated by a table of values, see Table II. Note that the recommended division resembles closely that based on square-root of transmission for which: $100\ T_{min}=0.92\ D^2$, $100\ T_{max}=0.92\ (D+1)^2$, where D is the digit indicating the transmission range from T_{min} to T_{max}.

most important because we have many filters which require two separate specifications in the red region (630 to 770 mμ) of the spectrum.

B. Subdivision of the transmission scale

Change in spectral transmission near zero produces a greater chromatic effect than the same change at high transmissions; for example, the stage designer will find that it is more important in the production of chromatic effects to have a yellow filter transmit nothing instead of one percent in the short wave part of the spectrum than it is to have it transmit 90 percent instead of 80 percent in the long wave part. It has been shown by Helson and Judd in work not yet completely published[2] that a change from one-tenth of one percent to zero in spectral transmission of a chromatic filter is easily detectable as a change in the surface color of the illuminated object. Accordingly, the original division of the scale[1] used the digit 0 to indicate the transmission range from zero to 0.001 (see Fig. 2). The ranges in transmission designated by the digits 1, 2, 3, 4, and 5 grew progressively larger in accord with the above generally accepted principle. The ranges designated by the other digits varied up and down in accord with no principle other than to have the division points fall upon easily expressible transmissions: 0.60, 0.70, and 0.80. This irregularity was criticized by Mr. Munsell who pointed out that it might give the false impression that changes in transmission near the middle of the scale are less important than those near the upper end. He also showed how this irregularity could be avoided without the use of inconveniently expressible division points (see Fig. 2).

TABLE I. *Designations of the 22 filters examined by Little and Parker.*

TRADE NAME	TRADE NUMBER	PROPOSED ISCC NUMBER
Pink Series		
Dark rose pink	7	5100999
Rose pink	6	7301999
Rose pink	39	7513699
Medium pink	37	8404799
Deep pink	8	8514999
Pink	5	8514999
Shubert pink	35	9616999
Medium pink	4	9735999
Dubarry pink	9	9754899
Flesh pink	3	9857999
Light flesh pink	2	9978999
Blue Series		
Daylight blue	25	9985448
Light sky blue	26	8875458
Light blue	27	9974217
Light navy blue	28	9952238
Special steel blue	29	8863337
Light blue special	30	8851004
Medium sky blue	31	8840003
Medium blue special	32	9850007
Medium blue	33	8720003
Medium navy blue	34	8710004
Dark sky blue	35	7710001

The next revision was made by Mr. Parker from an examination of the curves of spectral transmission of the 22 filters procured by Mr. Little. He noted that of this group of filters many would be better specified by using two digits in the transmission range 0.60 to 0.80 instead of 1; he proposed to do this by eliminating the use of two digits for the transmission range 0.00 to 0.01 which he described as a "little extravagant." The writer has attempted to defend his original use of two digits for this latter transmission range but without success. The pronounced effect found by Helson and Judd to be due to the admixture of one-tenth of one percent of stray light could not be demonstrated under practical conditions of illuminating a stage, apparently because one must expect at least one or two percent of stray light to be present. Furthermore, there were no pairs of filters among the approximately 50 measured which required this division of the transmission scale for their differentiation. Accordingly this feature of the Parker revision has been accepted as being a distinct improvement.

However, the upper portion of the transmission-scale division suggested by Parker shows, though in less degree, the same fault criticized by Munsell in the original scale. There has, therefore, been a further attempt to improve the division. As steps toward this improvement a logarithmic division of the transmission scale passing through 0.01 and 0.92 has been plotted (see Fig. 2) and a square-root division passing through 0.0092 and 0.92. A glance at the logarithmic division shows its complete unsuitability for the present purpose in spite of the frequency with which the term, logarithmic, is used to

[2] H. Helson and D. B. Judd, "A Study of Photopic Adaptation," J. Exp. Psychology **15**, 380 (1932); D. B. Judd, "Surface Color," J. Opt. Soc. Am. **25**, 44 (1935); H. Helson and D. B. Judd, "An Experimental and Theoretical Study of Changes in Surface Colors under Changing Illuminations," Psych. Bull. **33**, 740 (1936); H. Helson, "Tri-Dimensional Analysis and the Non-Film Modes of Color Appearance," J. Opt. Soc. Am. **27**, 59 (1937).

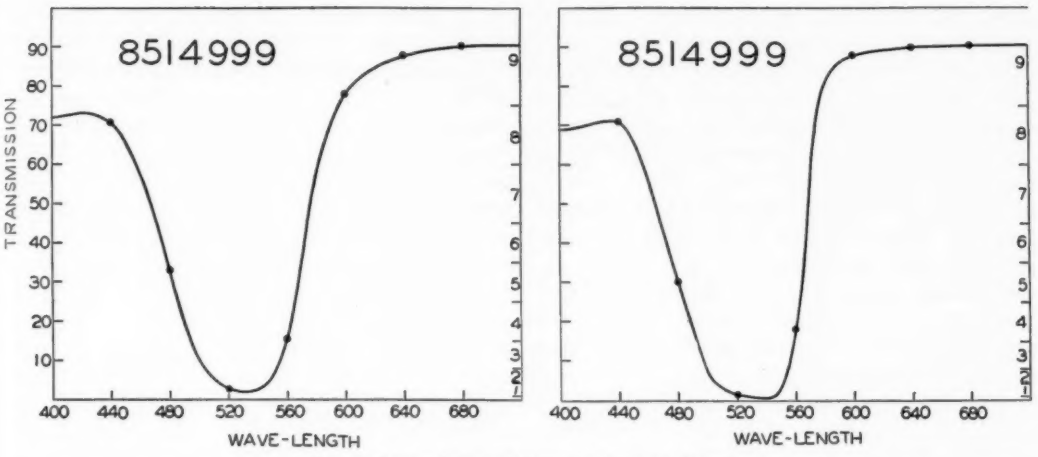

FIG. 3. Spectral transmissions of two pink filters.
They are now designated by the distributor: Deep Pink No. 8 and Pink No. 5; they both would receive proposed ISCC designation 8514999. This pair of filters illustrates closely the largest difference which can go undifferentiated by the proposed ISCC system of designation.

describe the ideal choice. The unsuitability comes from the fact that the logarithm of transmission varies over an infinite range as the transmission varies from 0 to 1. There is, therefore, no way to divide the transmission scale in a strictly logarithmic way into ten ranges; a lower part of the transmission scale must be chopped off. Even by this device, there is obtained a division of the transmission scale which is obviously unsuitable. These objections do not apply to the square-root division of the scale.

The recommended subdivision of the transmission scale is therefore based upon the square-root scale, and it embodies one further improvement which has so far not received explicit attention—the recognition that the practical upper limit of the transmission scale because of reflectance losses is about 0.92 instead of 1.00. The recommended subdivision may be described as a rounded-off square-root scale. The lower transmission limit designated by any digit is obtained approximately in percent by taking 0.92 of the square of the digit; of course, the upper limit is approximately obtained by taking 0.92 of the square of the next higher digit. From Fig. 2 it may be seen that the recommended scale includes all of the best features of the previously proposed scales.

In the discussion at the Council meeting it was suggested by A. G. Worthing, University of Pittsburgh, that if the 10-point subdivision of the transmission scale should prove to be not sufficient, use might be made of a scheme of mathematicians who deal with systems of more than ten digits and of genealogists who have to consider families in which there are more than ten children. In this scheme, the 11th member is designated, *P*; the 12th, *Q*; then *R*, *S*, *T*, and so on, up to whatever is necessary. Another suggestion was that the total number of designations might be raised to 13 by the addition of symbols: *J* (ack), *Q*(ueen), *K*(ing).

IV. Experimental Tests

The spectrophotometric curves of the 22 filters selected by Mr. Little were obtained on a General Electric automatic recording spectrophotometer. The designation by the system proposed was read from these curves directly and appears in Table I together with the manufacturer's name and number. All of the filters of the blue series were obtained from the same manufacturer. The pink series comprises filters from two manufacturers, filters Nos. 35, 37, and 39 from the second manufacturer being added to those of the first for the purpose of investigating the correspondence between filters with similar color names supplied by different manufacturers.

Examination of the proposed designations,

hereinafter called the proposed ISCC designations, for the two pairs of filters of the same name (medium pink and rose pink) shows immediately that there is not much correspondence. As might well have been expected, the filters bearing the same color name from different manufacturers differ considerably more than filters bearing different color names from the same manufacturer. Visual inspection of the filters corroborates this conclusion.

It will be noted that generally the proposed ISCC designations are quite definitely different for the different filters; it may be concluded therefore that the proposed system of designation is generally successful in differentiating between filters which have been found to be commercially different. This is true even for these two groups of filters particularly chosen because they contained many close visual duplicates for which it seemed legitimate to raise the question whether there is really a commercially important difference. However, two pairs of filters, one pink pair and one blue pair, are exceptions to this general conclusion and deserve special attention; they are Deep Pink No. 8 and Pink No. 5 for which the ISCC designations are identical (8514999) and Medium Blue No. 33 and Medium Navy Blue No. 34 for which the ISCC designations are 8720003 and 8710004, respectively. The spectral transmissions of these four filters are shown in Figs. 1 and 3.

As has already been mentioned, Fig. 1 shows the curves for the two blue filters, and the use of these filters reveals the fact that filter 8710004 brings out red objects somewhat more definitely than filter 8720003 as it would be expected to do from the notation. This was brought out as a part of a demonstration of these filters during presentation of the paper. A test object composed of 8 papers having highly selective pigment-coated matte surfaces was illuminated first by light through one filter, then the other. This pair of filters may be taken as an example of the smallest difference which will certainly be differentiated by the system of designation. It is a matter of opinion whether the filters themselves are characteristic of the smallest difference in chromatic effect which it is commercially desirable to differentiate, but it seems to many people that they are. The opinion that commercial tolerance is considerably larger than this difference, was expressed in discussion at the Council meeting by Charles Bittinger, Naval Research Laboratory and by Dean Farnsworth, New York University.

TABLE II

DIGIT	SPECTRAL TRANSMISSION
0	Less than 0.01
1	0.01 to 0.04
2	0.04 to 0.08
3	0.08 to 0.15
4	0.15 to 0.25
5	0.25 to 0.35
6	0.35 to 0.45
7	0.45 to 0.60
8	0.60 to 0.75
9	More than 0.75

It was suggested by Frederic H. Rahr, Color Consultant, that it would be a good idea to extend the test object used in evaluating subjectively the chromatic effect of the filters. He expressed the opinion that if gelatin transparencies and dyed fabric were to be used on the test object in addition to the pigmented papers actually used, that a different conclusion might have been reached and one more representative of stage illumination.

Figure 3 shows the curves for the two pink filters.[3] Note that there is a definite difference between the curves, that for the Pink No. 5 filter being considerably higher than that for Deep Pink No. 8 in the region 570 to 590 mμ. Since this principal difference happens to fall almost exactly in the center of one of the 40 mμ wave-length intervals, this pair of samples may be taken as representative of the largest difference between filters which would go undetected by the proposed ISCC system of designation. If it is considered by stage designers that the difference between these two filters is commercially important and that they would not be satisfied to accept one of the filters as a substitute for the other, then the proposed system of designation

[3] Following attention drawn by Gibson and Keegan (J. Opt. Soc. Am. **28**, 180 (1938)) to the inapplicability to fluorescent samples of spectrophotometers which, like the General Electric instrument, do not disperse the light after it leaves the sample, it was discovered that the Deep Pink No. 8 filter was definitely more fluorescent than the Pink No. 5 filter. The curves in Fig. 3, therefore, fail to show quite fairly the transmission differences between the two filters. However, the error is not sufficient to change the proposed ISCC designation for either.

would fail of its purpose and if it could not be modified to distinguish such pairs of filters the whole plan might as well be given up. Visual examination of test objects illuminated by light from these two filters, however, shows them to be but slightly different, the Deep Pink filter yielding a slightly more bluish pink than the Pink filter when both are used to illuminate a white screen. Chromatic test objects tried have failed to differentiate these two filters any more definitely. Since the actual difference found between the filters is different from the one to be expected from their names, it seems likely that the difference is too small to be of commercial importance.

V. Recommended Method of Specification

The method applies to all light filters for which more precise specification is unnecessary, but it is particularly useful for colored gelatins used in illumination of theater stages. The plan is to supplement the present designation of each filter by a seven-digit number, the first digit to refer to the spectral transmission at wave-length 440 mμ, the second at 480 mμ, the third at 520 mμ, and so on by 40 mμ steps up to the seventh digit, which refers to 680 mμ. The 7-digit number would be known as the ISCC number. Table II gives the meaning of the various digits. This division of the transmission scale is by square root rounded off to convenient values of transmission. The lower limit of transmission referred to by any digit is given in percent approximately by 0.92 times the square of the digit.

As an example, the filters shown in Fig. 3 would be known as Pink 8514999, in which "Pink" is included merely for its descriptive value, the proposed ISCC number being a sufficient specification.

The designations found by this system are, of course, not as complete as that by a curve of spectral transmission, but they may be easily written or telegraphed, and for purposes such as those indicated above will probably give a sufficiently complete specification.